VOLUME 1, No. 9 (1956)

NUCLEAR PHYSICS

MONTHLY JOURNAL DEVOTED TO THE EXPERIMENTAL AND THEORETICAL STUDY OF ATOMIC NUCLEI, NUCLEAR FIELDS AND THE FUNDAMENTAL ASPECTS OF COSMIC RADIATION

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NUCLEAR PHYSICS is published in monthly issues. The subscription price of a volume of 700 pages is fl 57.00; 114s; $ 15.00. Postfree.

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Printed in the Netherlands.

Nuclear Physics, North-Holland Publishing Co., Amsterdam, 1 (1956)

DETERMINATION OF THE K/β^- RATIO

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Received 24 May 1956

Abstract: A method for determining the relative probabilities of two competing types of radioactive decay—K-capture and β^--decay—is described. The method is based on a magnetic spectrometer investigation of the photoelectrons ejected by X-rays emitted as a result of K-capture and conversion of β^--decay γ-rays. The magnetic spectrometer ("coetron") and auxiliary experiments on photoelectrons ejected by X-rays emitted by various radioactive sources are described.

Results of measurements are presented for Au^{198}: $K/\beta^- < 10^{-4}$ and for Ir^{192}: $K/\beta^- = (4.5 \pm 1.0) \times 10^{-2}$.

1. Introduction

Among familiar atomic nuclei one may find triplets of neighbouring isobars, the first and the third isobars being stable, whereas the one situated in the middle is radioactive; for example: Os^{192}—Ir^{192}—Pt^{192} or Pt^{198}—Au^{198}—Hg^{198}. According to the known condition of stability of two neighbouring isobars the middle radioactive isobar should be expected to decay to both the first and third isobar. Thus, for Ir^{192} the ratio of the probabilities of transformation to Os^{192} (K-capture) or to Pt^{192} (β^--decay) is equal to a few percent. However, for Au^{198} and for some other isobar nuclei K-capture has not yet been detected. Observation of K-capture occurring in such cases and determination of its relative probability as compared with that of β^--decay is a matter of interest.

In the present work this problem was studied by investigating photoelectrons due to K-capture X-rays or to conversion of γ-rays following β^--decay. The study of the photoelectron spectrum was performed by means of a magnetic spectrometer. Groups of photoelectrons from K_α X-rays for elements corresponding to the first and third isobar could be satisfactorily resolved and their relative intensities measured. This kind of measurements provides the relative number of K-capture and β^--decay X-photons. On the other hand from the relative number of conversion electrons emitted in β^--decay one can find the number of X-photons per β^--disintegra-

tion. Hence it is possible to determine the quantity of K-captures per β^--disintegration.

The ratio of probabilities of K-capture and β^--decay may be computed from the following equation:

$$\frac{K}{\beta^-} = \frac{X_K}{X_{\beta^-}} \cdot \frac{W_{Z+1}}{W_{Z-1}} n_{\beta^-} - n_K . \tag{1}$$

Here n_{β^-} and n_K are numbers of conversion electrons (per β^--particle) from the K-shells of β^--decay and K-capture daughther atoms. These values can be determined immediately from the spectrum of conversion electrons and β-particles.

X_K/X_{β^-} is the ratio of intensities of K-series X-rays radiated during K-capture and β^--decay; one may confine one's consideration to the ratio of K_α-lines only, without taking into account the K_β-lines. Indeed

$$\frac{X_K}{X_{\beta^-}} = \frac{(K_\alpha+K_\beta)_K}{(K_\alpha+K_\beta)_{\beta^-}} = \frac{(K_\alpha)_K}{(K_\alpha)_{\beta^-}} \cdot \frac{(1+K_\beta/K_\alpha)_K}{(1+K_\beta/K_\alpha)_{\beta^-}} \approx \frac{(K_\alpha)_K}{(K_\alpha)_{\beta^-}}$$

as $(1+K_\beta/K_\alpha)$ is nearly constant for the change of the atomic number from $Z-1$ to $Z+1$.

W_{Z-1} and W_{Z+1} are the yields of fluorescence from K-levels of the K-capture and the β^--decay daughter atoms.

This procedure permits one to determine with relatively high accuracy the probability of K-capture in the cases when this probability is small. It is possible to attain such accuracy due to the fact that the probability of the K-capture is compared with that of some other weak effect (conversion of the γ-rays). Moreover, the advantage of this procedure consists in the possibility of using specimens with a relatively low specific activity when it is practically impossible to investigate the Auger-electrons. The lines of the photoelectrons from X-rays measured by means of a magnetic spectrometer are considerably narrower than the corresponding lines obtained in a scintillation spectrometer or proportional counter, and this permits one to interpret with greater reliability the observed lines. In many cases the photoelectric method may very well compete with the crystal diffraction method.

As an example of application of this method the investigation of the relative probabilities of K-capture and β^--decay was carried out for radioactive isotopes of iridium and gold: Ir^{192} and Au^{198}.

2. Spectrometer

Investigation of the spectrum of photoelectrons produced by X-rays was performed by means of a magnetic spectrometer with corrected focusing. We have called this kind of spectrometer the "coetron" which means "conversion-electron spectrometer." In

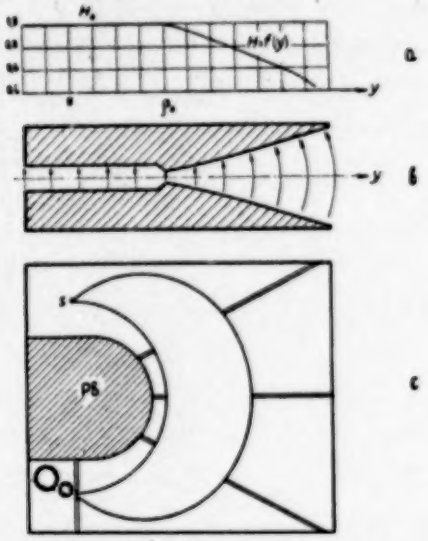

Fig. 1. A schematic drawing of a) theoretical curve of the magnetic field of the "coetron", b) the pole pieces of the "coetron", c) the electron paths in the "coetron" and spectrometer chamber.

order to improve the focusing of the electron beam we used in the "coetron" a non-homogeneous magnetic field which decreases along one axis of cartesian coordinates (y). The law of variation of the magnetic field and the character of focusing is illustrated in fig. 1, where magnet pole pieces and a vacuum spectrometer chamber are also shown schematically. The inner path of the electrons lies entirely in a homogeneous field. The outer paths partly (at $y > \varrho_0$) traverse a region of weaker fields and thereby the aberration characteristic for focusing in a homogeneous field is removed. A spectrometer of this kind makes it possible to obtain an exact focusing of a wide flat monoenergetic beam of electrons (for a point source). In the case of a space beam the focusing gets a little worse. A small "coetron" model ($\varrho_0 = 8$ cm) was previously described in detail. [1, 2])

In the present experiments a big "coetron" with a radius of the inner path $\varrho_0 = 20$ cm was used. The angles of divergence of the electron beam were equal to 30° in a horizontal plane and $\pm 3°$

in a vertical plane. The sources and the slit on the counter had the following dimensions: width 2 mm, length 3 cm, the apparatus width of the lines at half-maximum being $\Delta H\varrho/H\varrho = 0.5\ \%$.

A Geiger-Müller counter or two counters in coincidence were used to record the electrons. The film on the window of the first counter permitted electrons with energies $\approx$ 10 keV and higher to pass through. The device was evacuated to a pressure $\approx 10^{-5}$ mm Hg. Necessary measures were taken against selfcharging of the source. The source was mounted on a frame and was placed into

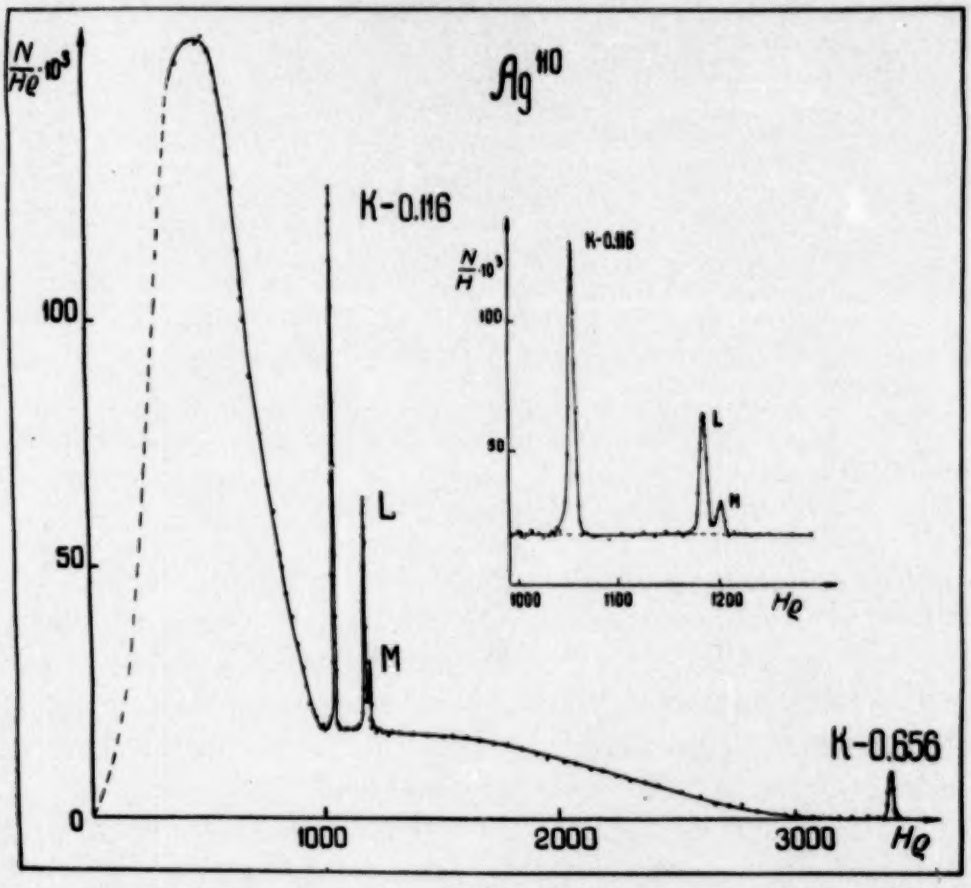

Fig. 2. Part of the β-spectrum of Ag^{110} in the energy region up to 0.6 MeV obtained by means of the "coetron". Sharp K-, L-, and M-conversion lines corresponding to the 0.116 MeV isomeric transition in Ag^{110}. In the insert a part of the spectrum including these lines is given in a changed scale.

the device in a strictly definite position without violating the vacuum in the spectrometer chamber. Energy calibration of the "coetron" was performed by using conversion lines of Th(B+C+C'+C''), annihilation γ-radiation and other accurately measured γ-lines. It was found that after carefully demagnetizing

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VOLUME I

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the spectrometer magnet the topography of the magnetic field would be unchanged at successive magnetising, and the intensity of the field H was more or less rigorously determined by the current i in electromagnet coils. It was thus possible to express the $H\varrho$ values of the observed electron lines in terms of the current. The errors in the determination of $H\varrho$ due to violation of a unique relation between the field strength H and the electromagnet current i and also errors due to inaccurate mounting of the source and to other causes on the average amount to 0.1 %.

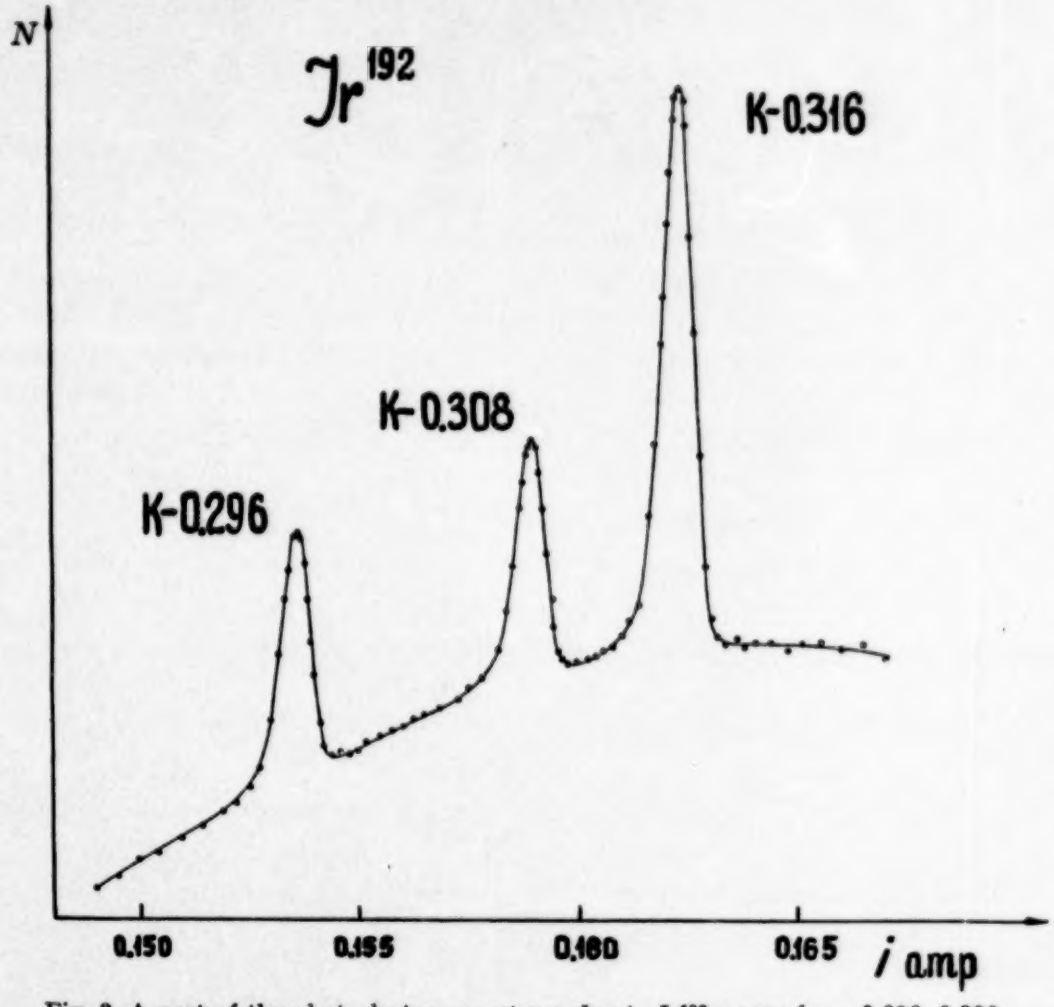

Fig. 3. A part of the photoelectron spectrum due to Ir^{192} γ-rays $h\nu$ = 0.296, 0.308 and 0.316 MeV as observed in the "coetron."

Operation of the "coetron" can be illustrated by the curves in fig. 2 and 3. Part of the β-spectrum and spectrum of conversion electrons of Ag^{110} in the region of energies up to 0.6 MeV are presented in fig. 2. The conversion electron lines from K-, L-,

and M-shells for the 0.116 MeV nuclear transition in Ag^{110} lie considerably higher than the remaining β^--spectrum and are resolved quite well. Part of the spectrum including these lines in a changed scale is illustrated in the insert of fig. 2. The width at the half-maximum of the lines is slightly greater than the apparatus width since a source of greater size was used during these measurements. The ratio of the number of K- to L-conversion electrons proved to be 2.1 ± 0.1, which agrees with our earlier measurement [3]).

In fig. 3 we show a part of the spectrum of photoelectrons ejected from a silver radiator by the γ-rays of Ir^{192} with energies 296, 308 and 316 keV. The width of the photoelectron lines at half-maximum are ≈ 0.5 %. Although the lines had rather close energies, they were resolved quite satisfactorily.

The properties of the "coetron" were verified during investigation of the β-spectra, and conversion electron and photoelectron spectra of the radioactive isotopes Zn^{65} [4]), Cs^{134} [5]), $Hf^{175, 181}$ [6]), Ir^{192} [7]), Ra(D+E) [8]), etc.

In the present experiment the source of photoelectrons for the investigation of X-rays was prepared as follows. The radioactive substance was pressed into a capsule of some light material in order to weaken the β-radiation. In most cases the capsule represented a tube as large as the focus of the spectrometer. The capsule was wrapped into the radiator foil from which the X-photons ejected photoelectrons. The radiator was made of silver foil 0.5 μ thick; thinner ones (≈ 0.1 μ) were obtained by covering the collodion films with silver by means of evaporation. The capsule with the radiator was placed in the spectrometer focus.

Under the above mentioned experimental conditions we observed besides the photoelectrons corresponding to the X-rays arising due to K-capture or to internal conversion of γ-rays also photoelectrons corresponding to the characteristic X-radiation of the initial radioactive atoms. This characteristic radiation is probably excited during the retardation of β^--particles and conversion electrons in the substance of the specimen. In order to confirm the interpretation of the photoelectron groups some auxiliary experiments were performed.

3. Auxiliary Experiments

In the first auxiliary experiment photoelectrons from X-rays excited only at the retardation of β-particles in the substance of

the specimen were studied. For this purpose a homogeneous mixture of bismuth powder and P^{32} were packed into a brass tube, the latter being wrapped into a silver foil (0.5 μ) and placed in the focus of the spectrometer. In fig. 4 one sees distinctly two groups of photoelectrons ejected from K-shells of silver atoms by $K_{\alpha 2}$ and $K_{\alpha 1}$ X-radiation of bismuth. The photoelectron groups cor-

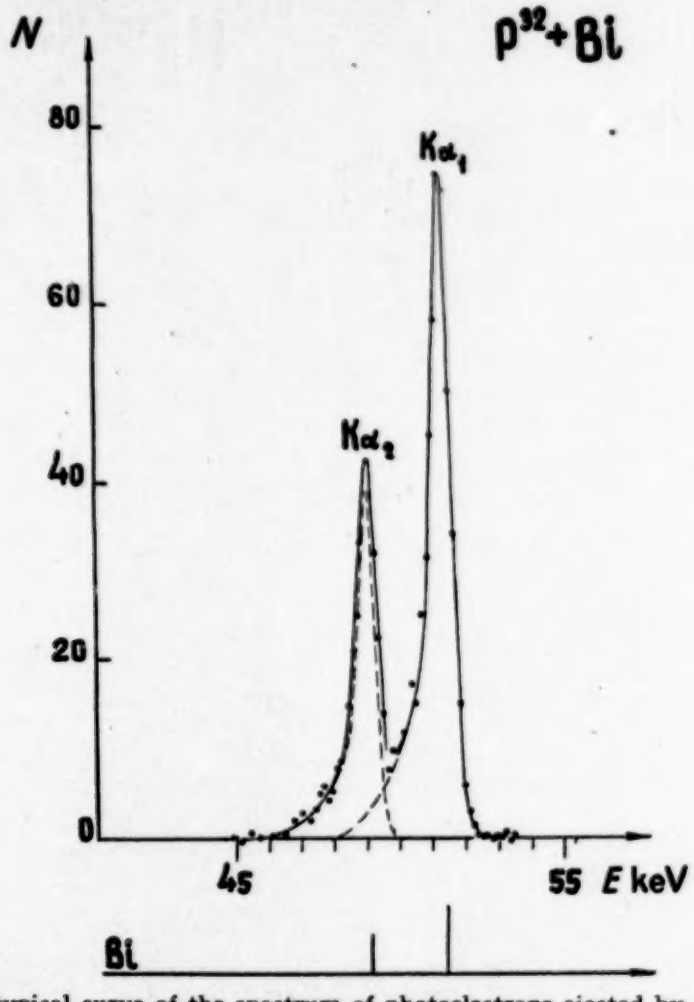

Fig. 4. A typical curve of the spectrum of photoelectrons ejected by Bi $K\alpha_2$ and Bi $K\alpha_1$ X-rays from K-shells of silver atoms (radiator 0.5 μ thick). X-rays of bismuth were excited by β-particles from P^{32}. The background has been subtracted. The expected photo-electron spectrogram is shown schematically under the curve.

responding to the K_β-X-radiation are situated in the spectrum at greater energies and they are not given in fig. 4. The background has been subtracted. The expected spectrogram computed from the X-ray data is schematically shown under the experimental curve. The perfect coincidence between the expected photoelectron lines

and those observed confirms the interpretation given. Hence, photoelectron lines from the characteristic X-radiation excited by β-particles in the substance of the specimen will be present in all the experiments of this kind.

In the second auxiliary experiment we observed photoelectrons from X-rays arising 1) from filling up the K-shells which contained

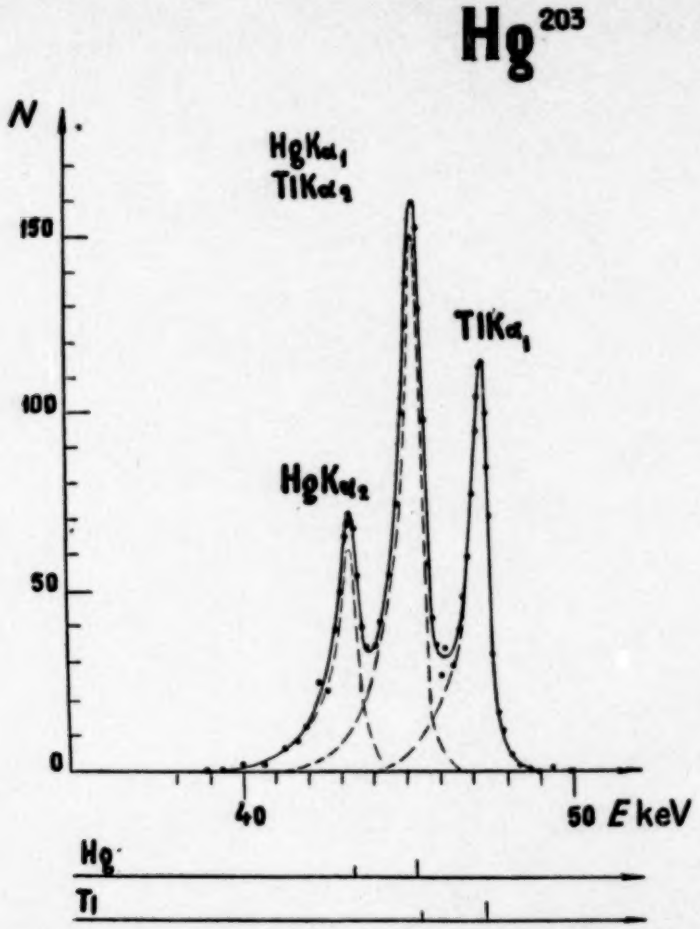

Fig. 5. A typical curve of the spectrum of photoelectrons ejected by the Hg $K\alpha_2$ Hg $K\alpha_1$, Tl $K\alpha_2$ and Tl $K\alpha_1$ X-rays from a silver radiator 0.5 μ thick. The X-rays are due to 1) bombardment of the mercury atoms by β-particles of Hg^{203} and 2) to conversion of the γ-rays emitted in the decay $Hg^{203} \rightarrow Tl^{203}$. The backgroud has been subtracted (compare with fig. 7 and 9).

a vacancy after a γ-ray conversion and 2) from the β-particle (and conversion electron) retardation already studied. The radioactive mercury isotope Hg^{203} was used in this experiment. Hg^{203} decays by 0.21 MeV β^--transition to the 0.28 MeV level of Tl^{203}. A silver foil 0.5 μ thick served as a radiator. In fig. 5 are distinctly seen three photoelectron groups ejected from K-shells of silver atoms

by $K\alpha_2$ and $K\alpha_1$ X-radiation of mercury and thallium. The Hg $K\alpha_1$ and Tl $K\alpha_2$ photoelectron lines merged into a single line. The expected spectrogram is given under the experimental curve.

In the third auxiliary experiment there were observed photoelectrons from X-rays due to 1) filling up of the K-atomic shell vacancies formed during conversion of β^--decay γ-rays; 2) filling up the K-shell vacancies due to K-capture; 3) retardation of the

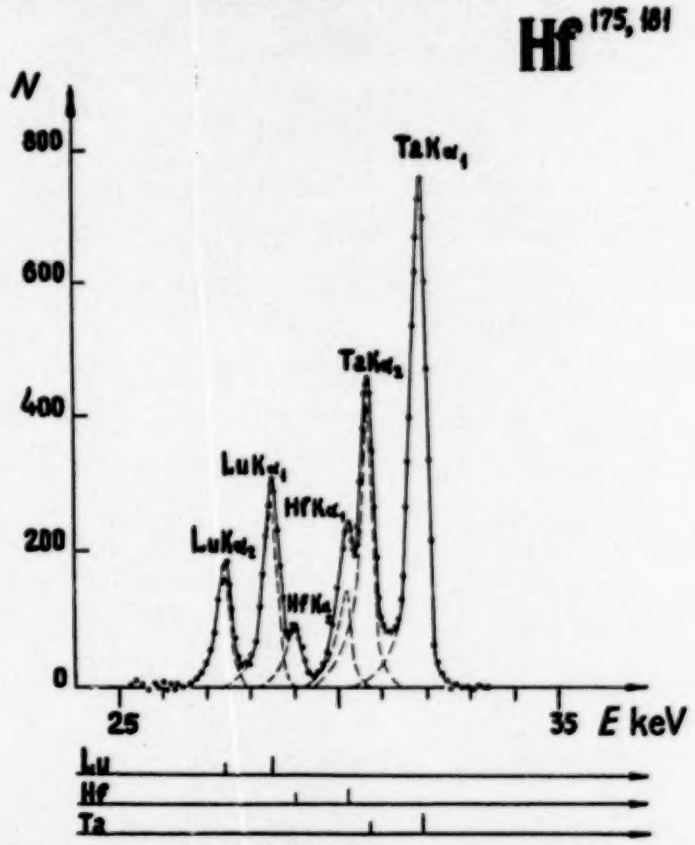

Fig. 6. A typical curve of the spectrum of photoelectrons ejected by $K\alpha_2$ and $K\alpha_1$ X-rays of lutetium, hafnium and tantalum from a silver radiator 0.1 μ thick. The X-rays are due to 1) the K-capture (Hf^{175}), 2) the bombardment of the hafnium atoms by β-particles and 3) the conversion of γ-rays emitted at the decay $Hf^{181} \rightarrow Ta^{181}$. The background has been subtracted (compare with fig. 7 and 9).

β^--particle and the conversion electrons. In these experiments we used a mixture of radioactive isotopes of hafnium, Hf^{175} and Hf^{181}; the former decays to Lu^{175} by K-capture, the latter, Hf^{181}, decays to Ta^{181} by β^--decay, a great number of K-conversion electrons [6]) being ejected in the last case. For these experiments the radiator was made by means of evaporating silver in vacuum. The thickness of the radiator was about 0.1 μ. In fig. 6 one can

detect six photoelectron groups ejected from the K-shells of silver atoms by the $K\alpha_2$ and $K\alpha_1$ X-radiation of lutetium, hafnium and tantalum. The expected spectrogram is given under the experimental curve. Here, as well as in the former cases, the agreement between the expected and observed lines of photoelectrons is very good.

The auxiliary experiments described above clearly show how one should interpret the spectrum of photoelectrons ejected by X-rays emitted from a radioactive specimen.

4. K/β^- Ratio for Ir^{192}

The radioactive decay of Ir^{192} has already been investigated in our earlier work [7]). The conversion spectrum indicated that part

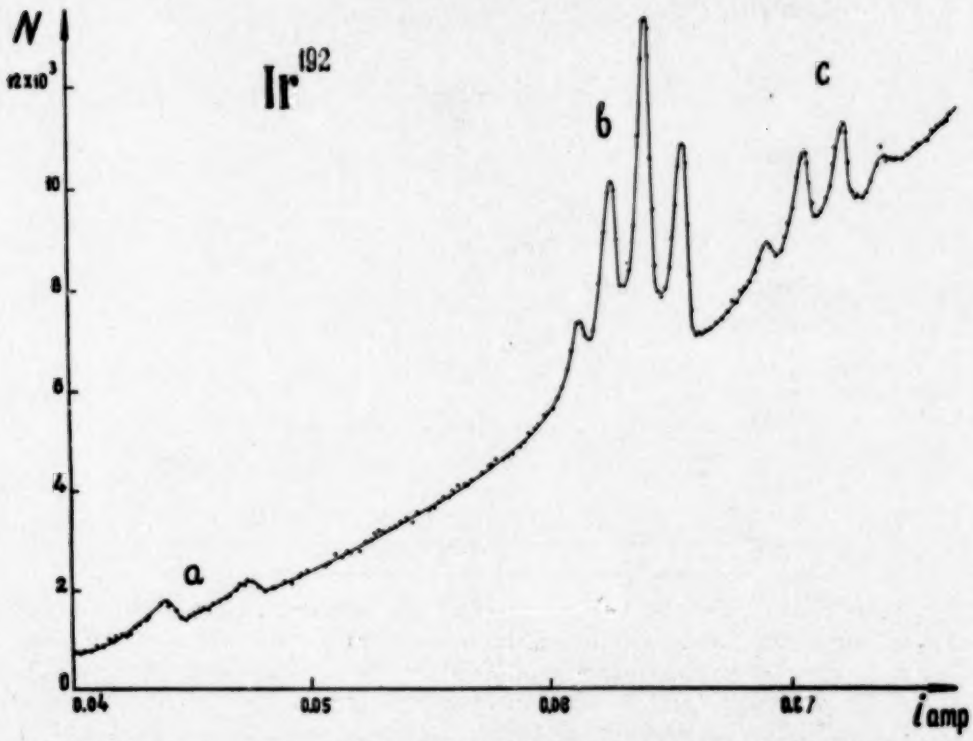

Fig. 7. A typical experimental curve of the spectrum of electrons emitted by a Ir^{192} specimen enclosed in a capsule wrapped in a 0.5 μ silver foil radiator. Here are (a) K—LL and K—LM Auger electrons from silver atoms, (b) photoelectrons from $K\alpha$ X-radiation and (c) photoelectrons from $K\beta$ X-radiation; the peaks (b) and (c) are due to the photoelectric effect in the K-shell of the silver atoms. The background (continuous spectrum) is due to the Compton-electrons and fast β-particles.

of the γ-rays was radiated in decay by capture of atomic electrons. Proceeding from the intensity of these γ-rays we came to the

conclusion that the relative probability of K-capture as compared to β^--decay was $\approx 4\ \%$. However, this deduction was based on the decay scheme $Ir^{192} \rightarrow Os^{192}$ which has not yet been fully established.

In the present work relative probabilities of K-capture and β^--decay were determined according to the method described above.

In this experiment layers of silver $\approx 0.5\ \mu$ and $\approx 0.1\ \mu$ thick

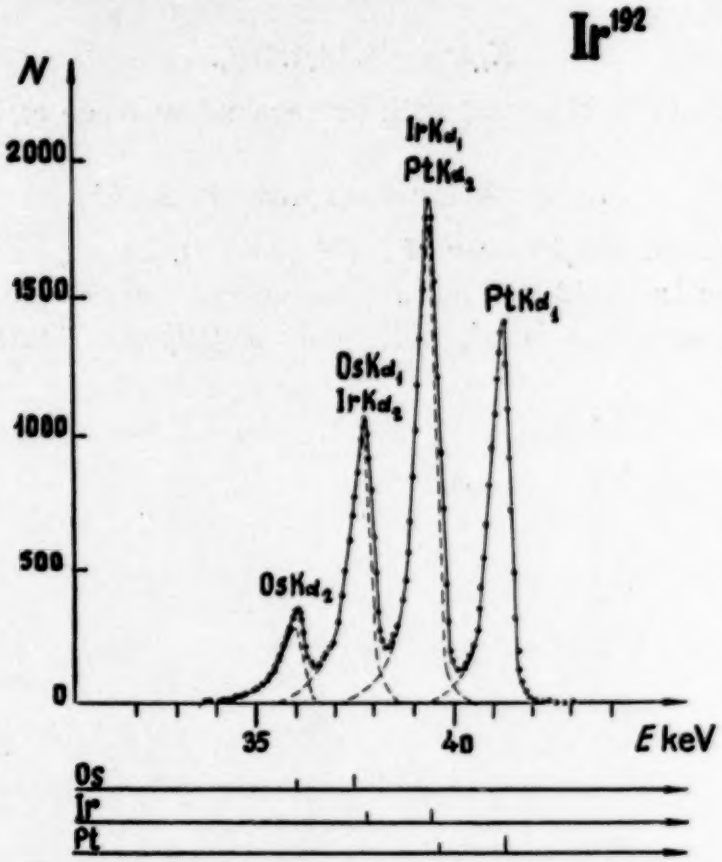

Fig. 8. A typical curve of the spectrum of photoelectrons ejected by the Kα X-radiation emitted by a Ir^{192} specimen from a silver radiator 0.1 μ thick. The background has been subtracted. The first two low energy peaks indicate the presence of K-capture in Ir^{192}.

served as radiators. The spectrum of photoelectrons ejected from K-shells of silver atoms by Kα X-radiation emitted by the specimen Ir^{192} is shown in fig. 7 and 8. The values of the energies of the lines observed and comparison of the curve in fig. 8 with those of figs. 4, 5, 6, clearly show that in this case K-capture took place. Photoelectron groups corresponding to the $OsK\alpha_2$ and $PtK\alpha_1$ X-lines are quite well resolved and permit one to determine the relative intensities of Kα X-radiation of Os and Pt. In carrying out the

computations by formula (1), the number of conversion electrons from the K-shells of the β^--decay and K-capture daughter atoms, n_{β^-} and n_k, were taken from the results of our investigation of the conversion spectrum [7]). It was moreover assumed that $(W_{Z+1}/W_{Z-1}) \approx 1$ and the effective cross sections for photoelectric absorption were taken into account. For the ratio of the probabilities of K-capture and β^--decay in the case of Ir^{192} we obtained the following:

$$K/\beta^- = (4.5 \pm 1.0)\%.$$

This result is in accord with our evaluation made earlier [7]).

5. Search for K-capture in Au^{198}

We studied the β^--decay of Au^{198} earlier [9]). Lately, besides the γ-ray line $h\nu = 412$ keV nuclear transitions in Hg^{198} of small intensities were also found, which only slightly contribute to the

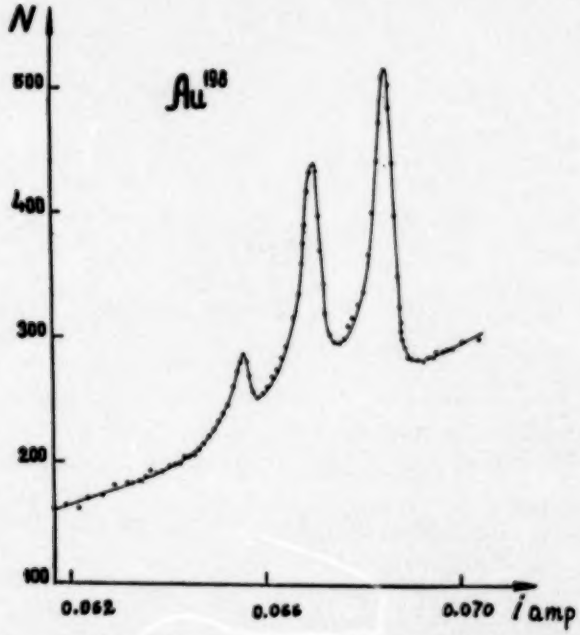

Fig. 9. A typical experimental curve of the spectrum of electrons emitted by a Au^{198} specimen enclosed in a capsule with a 0.5 μ silver foil radiator. The three peaks are due to the photoelectrons from Kα X-radiation.

number of conversion electrons. According to the existing data [10]) the disintegration of Au^{198} with capture of atomic electrons amounts to less than 0.4 %.

In the present work we made a search for K-capture decay of Au^{198} by using the above method.

A piece of gold foil 2—3 μ thick irradiated by neutrons was put on an aluminium plate, on the other side of which a 0.5 μ silver foil radiator was glued. The spectrum of photoelectrons ejected from the K-shells of the silver atoms by the Kα X-radiation emitted by a Au^{198} specimen is given in figs. 9 and 10. The energies of the three observed lines show that their origin is connected with internal conversion of γ-rays in β^--decay and with the bombardment of the substance of the specimen (gold) by β^--particles. Careful

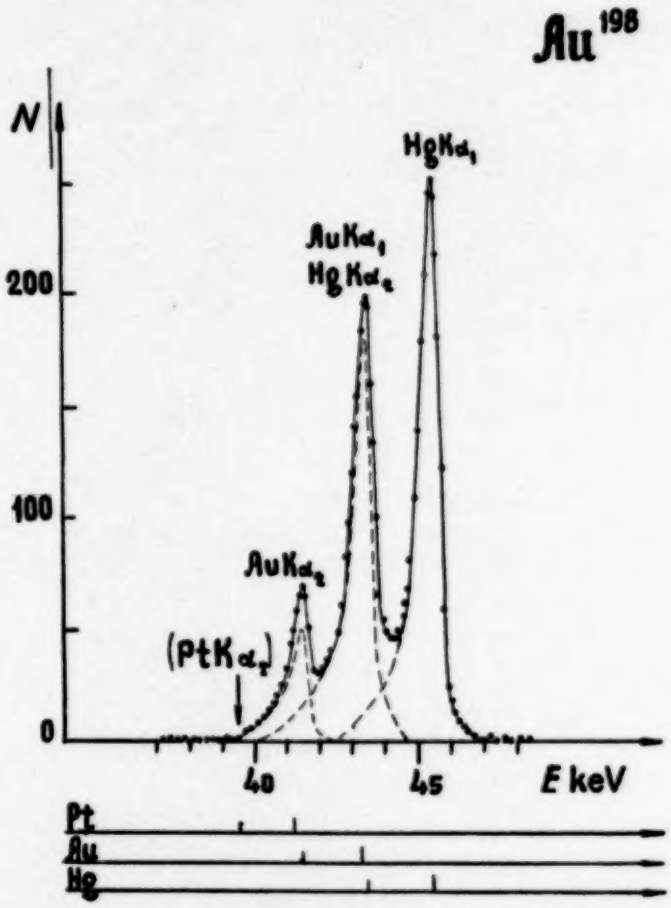

Fig. 10. The same as in fig. 9 but after the background has been subtracted. The arrow designates the place of the curve where the photoelectron peak corresponding to the K-capture in a Au^{198} should be located.

examination of the experimental curve did not reveal any traces of photoelectric lines, corresponding to K-capture.

By comparing the magnitude of the statistical measurement errors of that portion of the curve, where a $PtK\alpha_2$ photoelectron line was expected with the height of the $HgK\alpha_1$ photoelectron peak,

we could conclude that the upper limit for the probability of the K-capture decay of Au^{198} amounted to about 0.01 %:

$$K/\beta^- < 10^{-4}.$$

In such a way, the high sensitivity of the method has permitted us to appreciably decrease the upper limit for the probability of K-capture in Au^{198}.

The measurements were performed in collaboration with N. M. Antonieva and B. V. Pshenichnikov [11]).

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THE ISOMER Pb^{204m}

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Received 1 June 1956

Abstract: The conversion lines following the decay of Pb^{204m} have been studied in a double-focusing β-spectrometer and a semicircular permanent magnet β-spectrometer. The half-life of the isomer has been remeasured, and the value 67.5 ± 0.5 min obtained. The energies of the previously known gamma transitions have been reinvestigated and are 911.7 ± 0.3, 374.7 ± 0.4 and 899.3 ± 0.3 keV. The maximum amounts of M6 resp. M3 admixtures in the 911.7 keV E5 and 374.7 keV E2 transitions are found to be 0.5 % in both cases. Two new weak gamma rays have been found with energies 289.4 ± 0.2 and 622.2 ± 0.2 keV, the latter being an E5 transition emitted from the isomeric 9— level to a new 4+ level. Our experiments unambiguously suggest the following level sequence: 0 (0+), 899.3 (2+), 1274.0 (4+), 1563.4 (4+) and 2185.7 (9—) keV. The experimental level scheme is compared with the theoretical predictions by W. W. True.

1. Introduction

The isomer Pb^{204m} has been the subject of several investigations. The work of Sunyar *et al.* [1]) and Maeder *et al.* [2]) indicated that the 1.1 h activity in lead decayed via two gamma transitions in cascade, the first one being an E5 transition of 910 keV and the second one a 374 keV E2 transition. The half-life of the intermediate state was found to be 3×10^{-7} sec. On the other hand, Frauenfelder *et al.* [3]) suggested that the isomeric gamma ray was probably an E4+M5 mixture. Apart from this there were other difficulties in the interpretation of the decay scheme, and these are fully discussed by Maeder *et al.* [2])

In the course of angular correlation measurements, Krohn and Raboy [4]) discovered that the 910 keV gamma ray is, in fact, a doublet and suggested a decay-scheme with the following excited levels: 899 (2+), 1274 (4+), and 2186 (9—) keV. Their result was confirmed by Bergkvist *et al.* [5]), who gave the energies concerned as 913.0 and 899.3 keV. These were identified as E5 and E2 respec-

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tively on the basis of their conversion intensities. An attempt by Sunyar [6]) to measure the half-life of the 899 keV E2-transition has given a value of $< 6\times10^{-10}$ sec.

Krohn and Raboy [4]) concluded that the only possible spin assignments for the levels concerned were those mentioned above, but that with these assignments it was necessary to assume that the 912 keV gamma ray is 99 % E5+1 % M6 and that the 375 keV gamma ray is 99.5 % E2+0.5 % M3. In this case the ratio of the probabilities for M6 and E5 transitions between the 9— and 4+ states would be 10^{-2}, whereas the ratio of the corresponding approximate theoretical transition probabilities is [7]) 4×10^{-8}. Admittedly such a comparison is questionable because the electrical transitions are certainly not due to a single proton, but the discrepancy of a factor of 4×10^{-6} does seem too large, particularly in view of the fact that the same theory gives a half-life of the right magnitude ($\approx$ 40 min) for a pure E5 transition between these states. In the case of the 375 keV transition, the above admixture gives a ratio between transition probabilities of 5×10^{-3}, compared with a theoretical value of 2×10^{-7}.

Since the conversion coefficients of an M6 transition are expected to be very much greater than those of an E5 transition of 912 keV, it is expected that even the small admixture reported by Krohn and Raboy [4]) may effect the observed conversion coefficients of this particular gamma ray (see table II, page 651). While it may not be possible to measure conversion coefficients absolutely with sufficient precision to detect the admixture, the ratios between the intensities of conversion lines can be determined with high accuracy, and relative conversion coefficients calculated. A measurement of the ratio K_{912}/K_{899} should provide the required information. The ratio $(L_I+L_{II})/L_{III}$ is rather more sensitive to the M6 admixture in the 912 keV transition, but is more difficult to measure since (a) the fractional momentum separation between the L_{II} and L_{III} lines at this energy is 1.8×10^{-3}, so that a spectrometer resolution of about 0.1 % would be needed to resolve these lines, and (b) the lines $(L_I)_{912}$ and M_{899} are less than 1 keV apart so that an estimate of $(L/M)_{899}$ is needed to correct the $(L_I+L_{II})_{912}$ intensity.

In the case of the 375 keV gamma ray, a 0.5 % M3 admixture increases the intensity ratios K/L and $(L_I+L_{II})/L_{III}$ by only 3.5 % and 4 % respectively, so that a good deal of labour would be required to measure either of these ratios with sufficient accuracy

to detect so small an admixture. A measurement of the ratio K_{375}/K_{899} should also here give the desired information.

Recently W. W. True [8]) has made a theoretical calculation of the energy levels and particle configurations in Pb^{204} on the basis of the work of Alburger and Pryce [9, 10]). A large number of levels are predicted which should be populated in the decay of Pb^{204m}. Already in 1954 we observed some very weak conversion lines which might belong to Pb^{204m}. Because of the theoretical interest of levels in Pb^{204} a reinvestigation of these weak conversion lines seemed important.

2. Source Preparation

The Pb^{204m}-activity was in most cases produced by bombarding Tl with 25 MeV deutrons in the 225-cm cyclotron of the Nobel Institute. Strong activities of Pb^{202m} and Pb^{203} were also produced. Spectroscopically pure Tl metal was used, and in order to avoid impurities from soldering flux, the Tl metal was melted onto the targets with high-frequency heating in a hydrogen atmosphere. After irradiation, a thin layer of Tl was scraped off and dissolved in hot HNO_3, Fe-carrier added, and $Fe(OH)_3$, carrying the active Pb with it, precipitated with NH_3-gas, centrifuged off and washed. The precipitate was then dissolved in 6 *N* HCl and the Fe removed by at least three extractions with ether saturated with 6 *N* HCl. The activity was then evaporated in vacuum with a special evaporation device [11]) which had an efficiency of 85 % for a source of the size 2×12 mm^2 (for the double-focusing spectrometer) and 70 % for the size 0.2×13 mm^2 (for the semicircular spectrometer). For sources in the double-focusing spectrometer (radius = 50 cm) backings of thin Al-foil (0.15 mg cm^{-2}) were used, while for the semicircular spectrometer the activities were evaporated onto a Cu-wire of diameter 0.2 mm. In order to be able to detect weak lines, samples with a maximum strength of 2.5 C Pb^{204m} were produced.

Some measurements of conversion lines were carried out on a Bi-sample containing Bi^{204}. For this purpose lead was bombarded with 50 MeV protons in the Uppsala synchrocyclotron. The active Bi was then separated from the target material in a procedure described by Stockendal *et al.* [12]). For the half-life measurement Pb was milked from the Bi-activity in an ion-exchange column in order to get the Pb-activity as free as possible from other activities. This procedure is also described by Stockendal *et al.* [12]).

3. Results

3.1. HALF-LIFE MEASUREMENTS

It soon became evident that since the time taken to cover one of the conversion lines with any accuracy was of the order of half the half-life of Pb^{204m}, it was necessary to have an accurate measurement of this half-life. The Pb-activity was milked from Bi by the ion-exchange procedure referred to above. The bismuth isotopes expected to be present were Bi^{202} (95 min), Bi^{203} (12.3 h) and Bi^{204} (13.5 h) all of which decay to lead isomers and isotopes. A day was allowed to elapse so that substantially no Bi^{202} was left, and the column washed carefully to remove any traces of Pb^{202m} (3.7 h). Then further milkings would be expected to contain only Pb^{204m} and Pb^{203} (52 h).

Since the highest energy gamma ray occurring in the decay of Pb^{203} is[13]) the weak one of 680 keV, a scintillation spectrometer with its discriminator set to accept only pulses from the 899—912 keV doublet in Pb^{204m} should give the half-life of this isomer. In order to obtain an accurate result in such a measurement, it is necessary to ensure that there is no drifting of the scintillation spectrum. The stabilizer designed by de Waard [14]) is eminently suited to this purpose, provided a strong, long-lived peak is available in the spectrum. To provide this, a source of Cs^{137} was introduced, the 662 keV gamma ray from which did not interfere with the part of the spectrum to be studied.

The scintillation spectrum of a trial milking together with the Cs^{137} source is shown in fig. 1. The decay curve taken with the discriminator set at 48 volt is shown in fig. 2. The curve shows a long-lived background with a half-life estimated at (42 ± 10) hours. This background might be due to a gamma ray of about 1.4 MeV, but only a very rough estimate of this energy was possible.

After correction for this component, the points could be fitted unambigously by a straight line, and the half-life was found to be

$$T_{\frac{1}{2}(Pb^{204m})} = 67.5 \pm 0.5 \text{ min.}$$

3.2. PREVIOUSLY KNOWN GAMMA RAYS OF ENERGIES 375, 899 AND 912 keV

a. Energy determinations: The groups 899 K, 912 K, 899 L and 912 L were measured several times in the double-focusing spectrometer at resolutions ranging from 0.14 % to 0.30 %. The 912 L group was

measured once at a resolution of 0.12 %. figs 3 and 4 show the appearance of some of these lines at the higher resolutions.

The energies of the conversion lines were measured in each run, the calibration of the spectrometer being checked each time against the standard conversion lines of Cs^{137} and Bi^{207}. The energy of the

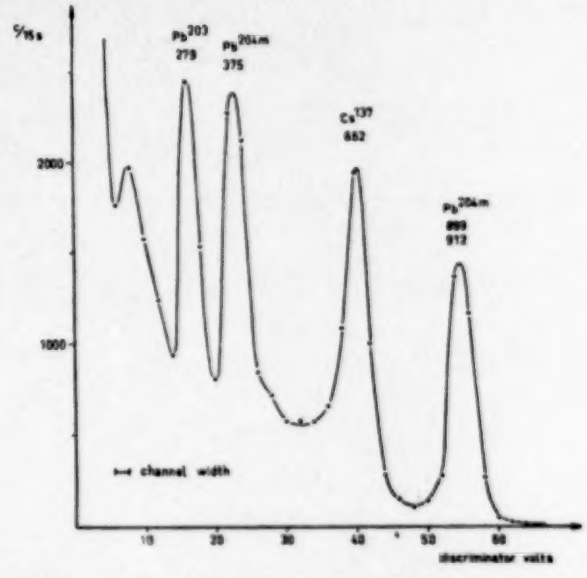

Fig. 1. Scintillation spectrum of source used for measuring half-life of Pb^{204m}. The Cs^{137} source was introduced for the operation of the stabilizer.

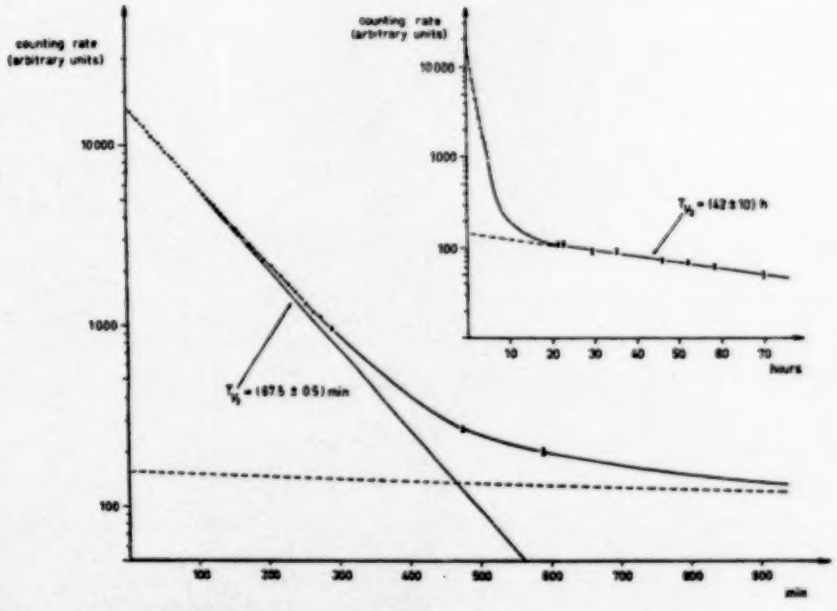

Fig. 2. Half-life of Pb^{204m} measured with a scintillation spectrometer accepting all energies > 775 keV. The inset shows the decay-curve in a compressed scale illustrating the long-lived background. The non-decaying background has been subtracted.

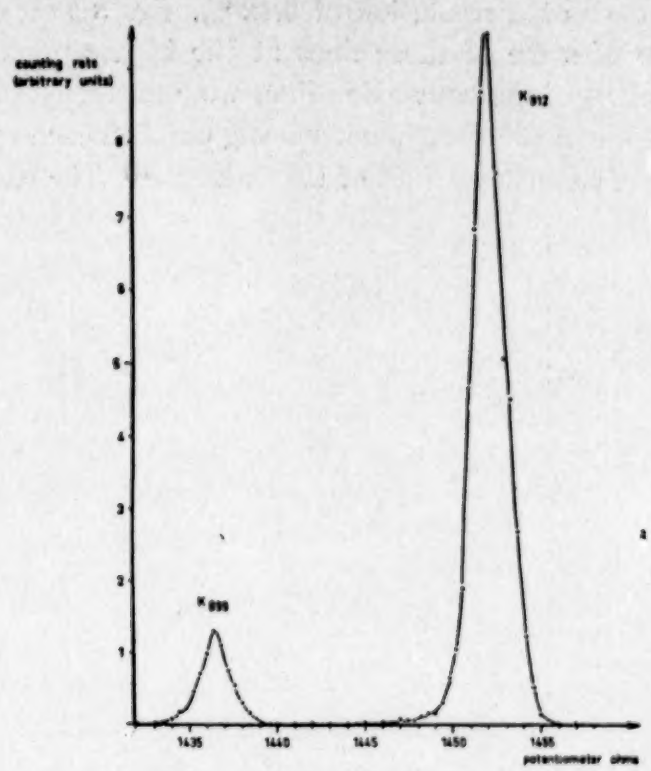

Fig. 3. K-conversion lines of the 899 and 912 keV gamma rays — after correction for decay and subtraction of the background. Resolution: 0.15 %. The statistical errors in counting rate are about 2 % on the peaks.

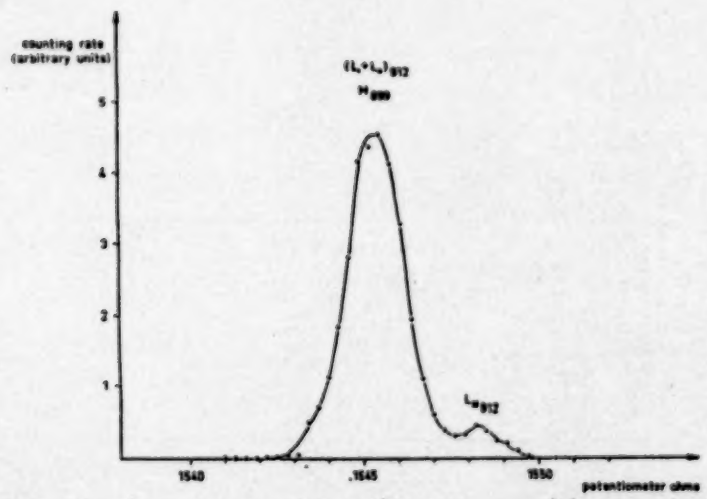

Fig. 4. L-conversion lines of the 912 keV gamma transition. — Corrected for decay and background. Resolution: 0.12 %. The statistical errors in counting rate are about 2 % on the peaks.

375 keV gamma ray was obtained in other experiments concerned with the decay of Bi^{204}. The energies found for the three gamma rays are thus:

$$911.7 \pm 0.3 \text{ keV},$$
$$899.3 \pm 0.3 \text{ keV},$$
$$374.7 \pm 0.4 \text{ keV}.$$

b. Energy of the first excited state in Pb^{204}*:* Both angular correlation measurements [4]) and our conversion measurements (see below, *c* and *d*) definitely show that the 375, 899 and 912 keV gamma rays are predominantly of multipolarities E2, E2 and E5 respectively, and that the level sequence is 0+, 2+, 4+ and 9−. However, these measurements do not satisfactorily prove which gamma ray, the 375 keV or the 899 keV, is emitted between the 2+ and 0+ states. Coincidence measurements [4]) showed that both of these gamma rays are emitted in cascade from a 0.3 μs 4+ state. It is more probable that the 375 keV gamma ray determines the half-life of the 4+ state because of its lower energy, though this is not a convincing proof. In order to settle this question, we have measured the intensity ratio K_{375}/K_{899} in the decays of Pb^{204m} and Bi^{204} and obtained the following values:

$$(K_{375}/K_{899})_{Pb^{204m}} = 6.4 \pm 0.4 \text{ (cf. 3.2}d\text{)}$$
$$(K_{375}/K_{899})_{Bi^{204}} < 2.5.$$

In the decay of Pb^{204m}, the 2+ state is fed only from the 4+ state, while in the decay of Bi^{204} there may be other possibilities of feeding. The values above show that in the decay of Bi^{204} the 899 keV transition is more intense than in the decay of Pb^{204m}. This unambiguously shows that the 899 keV gamma ray is emitted after the 375 keV gamma ray, and thus between the 2+ and 0+ states. For this reason the 899 keV gamma ray is a pure E2 transition, a fact which will be used when discussing possible admixtures of magnetic radiation in the 375 and 912 keV transitions.

c. Multipolarity assignments: To obtain information on the multipolarities of the 375, 899 and 912 keV transitions we have measured (K/L)-ratios, K-conversion ratios (3.2*d*) and the $[(L_I+L_{II})/L_{III}]$-ratio of the 912 keV transition. By taking the weighted means of the values obtained in various runs, we find the (K/L)-ratios given in table I, in which they also can be compared with theoretical values (according to Rose *et al.* [15])).

TABLE I

γ-ray	$(K/L)_{exp}$	$(K/L)_{theor.}$
375	1.76±0.1 †	1.8†† (E2)
899	3.9 ±0.4	4.63 (E2)
912	1.7 ±0.8	1.63 (E5)

† K/(L+M+ . . .), according to Maeder *et al.* [2]).
†† K/(L+M+ . . .), assuming L/(M+N+ . . .) ≈ 3

As can be seen from table I the assumed multipolarities E2, E2 and E5 seem probable, as proposed by Krohn and Raboy [4]). Moreover the $[(L_I+L_{II})/L_{III}]$-ratio of the 912 keV transition is found to be

$$[(L_I+L_{II})/L_{III}]_{912} = 11\pm2$$

compared with the theoretical value 12.7 for a pure E5 transition (Rose *et al.* [15])). This also supports the E5 assignment. The 899 keV transition has to be a pure E2, as it is emitted between the 2+ and 0+ states.

Further reasons for the proposed multipolarities are given in the next section, where the conversion coefficients for the 375 and 912 keV transitions are calculated.

d. Possible admixtures of magnetic radiation in the 375 *and* 912 keV *transitions:* If the level scheme of fig. 6b is accepted, then the ratio between the transition intensities (K+L+M+ . . . +γ) of the 912, 375 and 899 keV transitions must be 0.9973 : 1 : 1 and thus

$$\frac{K_{912}}{0.9973}\left[1+\left(\frac{L+M+\ldots}{K}\right)_{912}+\frac{1}{\alpha_{912}}\right] = K_{375}\left[1+\left(\frac{L+M+\ldots}{K}\right)_{375}+\frac{1}{\alpha_{375}}\right] = K_{899}\left[1+\left(\frac{L+M+\ldots}{K}\right)_{899}+\frac{1}{\alpha_{899}}\right].$$

Using our experimental values given in subsection 3.2*c* and assuming that L/(M+N+ . . .) ≈ 3 (this value is not critical) we can write these equations [$\alpha_{K_{899}}(E2) = 0.00653$, Sliv *et al.*[17])]

$$\frac{1}{0.9973}\times\frac{K_{912}}{K_{899}}\left[1.78+\frac{1}{\alpha_{912}}\right] = \frac{K_{375}}{K_{899}}\left[1.57+\frac{1}{\alpha_{375}}\right] = 154.4.$$

The ratio K_{912}/K_{899} has been measured and the ratio K_{375}/K_{899} can be calculated from the value of

$$\frac{K_{912}+K_{899}}{K_{375}} = 1.35\pm0.7$$

given by Maeder *et al.* [2]) and our value of K_{912}/K_{899}. The values obtained are

$$K_{912}/K_{899} = 7.7\pm0.2$$
$$K_{375}/K_{899} = 6.4\pm0.4.$$

Thus it is possible to determine the conversion coefficients for the 375 and 912 keV gamma-rays and to estimate the admixture of magnetic radiation. The conversion coefficients thus obtained are given in table II, and compared with the theoretical values for E5 and E2 radiation. We have also calculated the conversion coefficients of the admixtures (99 % E5 + 1 % M6 and 99.5 % E2 + 0.5 % M3 resp.) proposed by Krohn and Raboy [4]), and, as shown in the last column, the admixtures found in our experiments.

TABLE II

γ-ray	Exp. α_K	Theoretical α_K †		Exp. admixture
375	$(4.44\pm0.29)10^{-2}$	3.93×10^{-2} (E2)	4.67×10^{-2} (99.5 % E2+0.5 % M3)	(0.34±0.2) % M3
912	$(5.49\pm0.20)10^{-2}$	5.49×10^{-2} (E5)	5.94×10^{-2} (99 % E5+1 % M6 ††)	(0.0±0.45) % M6

† Calculated from Sliv *et al.* [17]) (The K-conversion coefficients are corrected for the finite size of the nucleus).

†† The M6 coefficients were found by extrapolation.

As can be seen from table II the M6 admixture in the 912 keV E5 transition is < 0.5 %, and thus smaller than the value 1 % suggested by Krohn and Raboy, whereas we cannot fully exclude an admixture of 0.5 % M3 radiation in the 375 keV E2 transition, which has been previously suggested by the same authors.

3.3. NEW WEAK GAMMA RAYS OF ENERGIES 289 AND 622 keV

The existence of weak conversion lines was established by an exposure in a semicircular permanent magnet with a source strength of $\approx$ 1 mC Pb^{204m}. These lines were then carefully studied with a resolution of 0.3 % and a source of $\approx$ 2.5 mC Pb^{204m} in the double-focusing spectrometer. As can be seen from fig. 5 the new conversion lines have considerable counting rates, though their intensities are weak compared with previously known lines. The experimental results are summarized in table III.

TABLE III

Line	E_{e^-} (keV)	I_{e^-} (rel.)	E_γ (keV)	$T_{\frac{1}{2}e^-}$ (min)
K 289	201.4†	1.92±0.13	289.4±0.2	64 ±4
K 622	534.3	0.70±0.07	622.3±0.2	64 ±5
L_{II} 622	606.9	0.95±0.07	622.1±0.2	66 ±5
M 622††	619.0		622.9±1.0	
K 899	811.3	13.0 ±0.4	899.3±0.3	67.5±0.5
K 912	823.7	100	911.7±0.3	67.5±0.5

† This line has also been observed by the Berkeley group (Fritsch). Private communication from G. T. Seaborg.

†† Measured on a photographic film only.

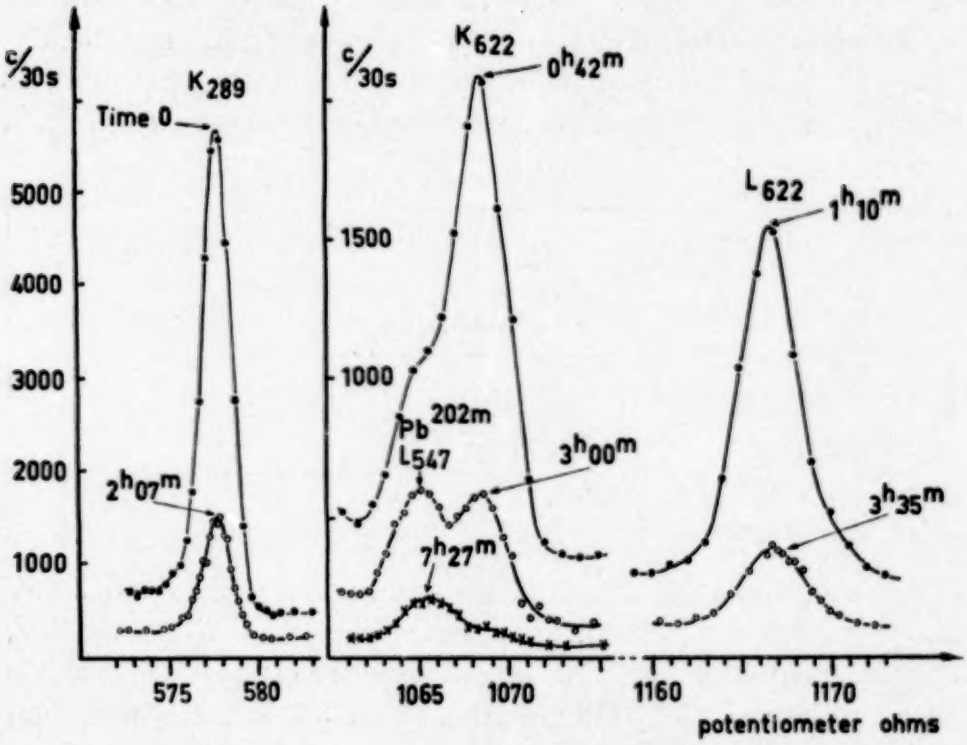

Fig. 5. Conversion lines K_{289}, K_{622} and L_{622} (the K_{622}-line is partly hidden by a 3.7 hr Pb^{202m}-line). Resolution: 0.3 %.

The conversion line at 201.4 keV is believed to be a K-line. The position of its corresponding L-line is obscured by other lines. However, in the decay of Bi^{204} there is a strong line of the same energy which certainly is a K-line (L-line also visible) of a 289 keV gamma ray, which, because of its K/L ratio ≈ 5 and K-conversion coefficient > 0.1 should be mainly of M1 multipolarity [16]).

As can be seen from table IV the K/L ratio of the 622 keV gamma ray suggests the multipolarity E5.

TABLE IV

	M4 †	E4 †	M5 †	E5 †	Exp.
K/L	2.76	1.31	2.03	0.84	0.74±0.09

† According to M. E. Rose *et al.* [15])

The sum of the energies of the two new gamma rays is 911.6 keV as compared with the energy 911.7 keV for the well established E5 gamma ray. This strongly suggests that the 622 keV gamma ray is emitted from the 9− level to a new 4+ level (fig. 6 b) from which the 289 keV gamma ray is emitted to the 4+ level previously known. If the new 4+ level is de-excited mainly by the emission of the 289 keV gamma ray, the total intensities of the 622 and 289 keV transitions must be the same. The transition intensities were calculated from the measured intensities of conversion electrons and the theoretical K-conversion coefficients of L. Sliv *et al.* [17]). As can be seen from table V the multipolarities E5 and M1 for the 622 and 289 keV gamma rays give, within experimental error, the same transition intensity. This means that an eventual transition from the new 1563 keV 4+ level to the 899 keV 2+ level must have a negligible intensity.

TABLE V

γ-ray	M1, E5	E2, E5	E1, E4	M2, E4
289	100	420	1030	53
622	82	82	150	150

From the K-conversion intensities in table II we calculate the transition probabilities of the two E5-transitions, and get

$$\frac{(K+L+M+\ldots+\gamma)_{912}}{(K+L+M+\ldots+\gamma)_{622}} = 374\pm40,$$

which means that only (0.27±0.03) % of all transitions from the 9− state goes via the 622 keV transition.

4. Discussion

The spin and parity assignments of the levels of Pb^{204} populated in the decay of Pb^{204m} are experimentally determined without ambiguity. It is therefore interesting to compare these levels with

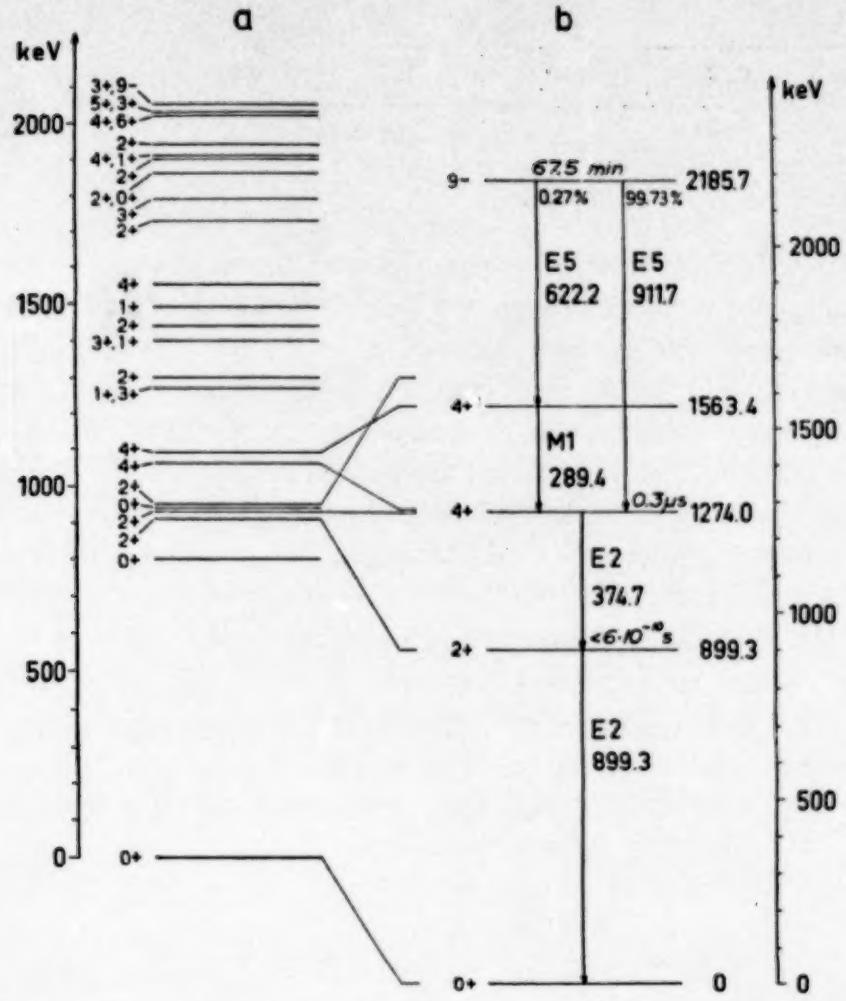

Fig. 6. a) Theoretically predicted levels in Pb^{204} with experimentally proposed level-splitting.
b) Experimentally found levels in the decay of Pb^{204m}.

those theoretically predicted by True [8]) (fig. 6a). The lowest 2+ levels corresponding to the configurations $(f^3_{5/2},\ j = 5/2)p_{1/2}$, $p^2_{1/2}\, f^2_{5/2}$ and $(f^2_{5/2},\ j = 0)\ (p_{1/2}\ p_{3/2},\ j = 2)$ have energies 0.91, 0.93 and 0.95 MeV. The observed 2+ level at 899.3 keV may therefore be due to the configuration $f^3_{5/2}\, p_{1/2}$. The low lying 4+ levels have energies 1.06, 1.09 and 1.55 MeV and the corresponding configurations are $p^2_{1/2}\, p_{3/2}\, f_{5/2}$, $p^2_{1/2}\, f^2_{5/2}$ and $f^3_{5/2}\, p_{1/2}$ respectively.

At first sight it might be tempting to assign to the experimentally found 4+ levels at 1274.0 and 1563.4 keV the configurations $p^2_{1/2}\, p_{3/2}\, f_{5/2}$ and $f^3_{5/2}\, p_{1/2}$ respectively. The experimentally found 9— level at 2185.7 keV should correspond to the expected 9— level at 2.05 MeV due to the configuration $p^2_{1/2}\, f_{5/2}\, i_{13/2}$. Such assignments

would, for example, require the experimentally observed E5 transitions to be

$$p_{1/2}^2 f_{5/2} i_{13/2} \rightarrow p_{1/2}^2 p_{3/2} f_{5/2} \text{ and } p_{1/2}^2 f_{5/2} i_{13/2} \rightarrow f_{5/2}^3 p_{1/2}.$$

These transitions involve configuration changes of one and two holes respectively, and it may be expected that the latter transition is relatively slower than the former. The value $\gamma_{912}/\gamma_{622} \approx 400$ is obtained from the measured intensities of conversion lines and theoretical conversion coefficients. This should be compared with the value 67 for transitions of single protons [7]), indicating that the 622 keV γ-transition is relatively slower than the 912 keV γ-transition.

However, True did not take configuration interactions into account in his calculations. The fact that the energies of the 2+ level and the second 4+ level found experimentally agree with the theoretically calculated energies is for this reason probably accidental. According to the first order calculations, a large number of transitions should be seen in the decay of Pb^{204m} which, in fact, is not the case.

Several difficulties in comparing experiments with theory are avoided by assuming the observed 4+ levels to be identical with the lowest close lying pair of 4+ levels predicted by True. The experiments would then give the order of magnitude of the configuration interaction between the 4+ levels. In fig. 6 we have also roughly indicated how configuration interaction could split the 2+ levels and lower the 0+ ground state.

Thus, the reason for no other 2+ levels being populated with measurable intensities in the decay of Pb^{204}, may be that the positions of these levels, due to configuration interactions, are such that transitions from the 4+ levels are energetically of very small probabilities or impossible. Between the 9- and highest 4+ level True predicts a large number of levels which are not seen in our experiments. This is understood because most of the levels have spins < 4 and thus the transitions from the 9— level are much more forbidden than to the 4+ levels. Levels with spins ≥ 4 are predicted to be close to the 9— levels, and transitions to these levels should have a small probability because of the low transition energies involved. In the same way, transitions from a 2+ level to close-lying 0+ levels are much weaker than those to the 0+ ground state.

Finally it is worth noticing that the 65 μs isomer in Tl recently reported by Vegors and Axel [18]), which is probably Tl^{204m} [19]), is not populated by any measurable intensity in the decay of Pb^{204m}.

We would like to thank Dr H. Atterling and his cyclotron crew for the numerous bombardments necessary in these experiments and Professor K. Bleuler, Zürich, for valuable discussions about theoretical aspects of this work. One of us (J. A. McDonell) wishes to thank the Head of the Nobel Institute, Professor M. Siegbahn and other members of the Institute for their hospitality during his stay in Sweden.

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Nuclear Physics, North-Holland Publishing Co., Amsterdam, **1** (1956)

INVERSION IN THE ISOBARIC SPIN SPACE

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Received 7 May 1956

Recently d'Espagnat and Prentki [1]) proposed an axiomatic formulation of the Nishijima, Gell-Mann model for the unstable heavy particles. They started from the requirement that the strong interaction is to be formulated in an invariant way even for reflections in the isobaric spin space. In their paper, once the interaction Lagrangian was formed under this requirement, the concept of reflection in isobaric space disappeared behind the deductive course of argument. We shall show in this short note that an equivalent formulation can be carried out in a much simpler way and always in the light of the concept of reflection in isobaric space. Moreover we can get some insight into the distinction between the strong and the weak interactions.

[*Editor's note*

In the first part of his paper, Dr Murai proceeds to develop a characterization of isobaric parity and interpretation of the invariant U of d'Espagnat and Prentki, which, apart from unessential formal differences, proves to be identical with that given by G. Racah in a note recently published in this journal [2]). It has therefore been deemed unnecessary to reproduce this part of Dr Murai's paper; it suffices to note that he has independently arrived at results equivalent to those of Racah. We publish in full, however, the end of the paper, which is based on d'Espagnat and Prentki's theory and uses the terminology and notations of these authors.]

If we assign an even parity to the vacuum, the parity of states with even number of isofermions is determined. But the parity of states with odd number of isofermions cannot be compared with that of the vacuum, as these are $+i$ or $-i$ with respect to vacuum; so we have to assign an arbitrary parity (e.g., an even parity) to the one-nucleon state. Then each state has definite parity as listed below:

		no baryon	one baryon
I	I_+	Vac., π, (π, π), ...	Λ, Σ, (Ξ, θ), (Λ, π), (Σ, π), ...
	I_-	(θ, θ), (θ, θ, π), ...	(N, θ), (N, θ, π), $(\Lambda, \theta, \theta)$, ...
II	II_+	θ, (θ, π), ...	N, (N, π), (Λ, θ), (Ξ, θ, θ), ...
	II_-		Ξ, (N, θ, θ), (Ξ, π), ...

It is meaningless to compare the parity between states I and II. In fact if we form a linear combination $\Psi_I+\Psi_{II}$, where Ψ_I and Ψ_{II} belong to states I and II respectively, and operate on it an inversion twice, i.e. the identity operation, then it changes to $\Psi_I-\Psi_{II}$. Therefore the relative phase of these states is not observable and so we may say that between these two states there exists a superselection rule [3]). Of course the superselection rule holds if the symmetry in the isobaric spin space is really fundamental and in the real world a weak interaction connects these two states. It is interesting, however, to notice that the weak interaction occurs only by pushing the superselection rule aside and never occurs between states I_+ and I_- or between II_+ and II_-; so we may say that as far as the isobaric parity is properly assigned the conservation of parity forbids the weak interaction too †. It will be right to say that in the weak processes the number of isofermions changes by one.

The conservation of parity, baryon number, and charge cannot decide whether a given process is strong or weak (except for elementary processes), and we need a conservation of U. As we have seen the existence of U necessitated a severe restriction for the isobaric parity and there remains no room to introduce any other value of strangeness.

As the attempts at the classification of heavy particles are usually based upon the extension of charge independence, they are powerless in characterizing the decay interaction of heavy mesons into leptons, the concept of isobaric spin not being applicable to the lepton family. It will be a clue for future theory to search a formalism which replaces that of isobaric spin and is applicable both to baryons and leptons. The above formulation suggests that the classification of the heavy particles does not necessitate the full rotation group in the isobaric spin space, since so far as the elemen-

† This corresponds to the interaction for which $\Delta U = \pm 2$, and processes such as $\Xi \to N+\pi$, and $N+N \to \Lambda+\Lambda$ are to be regarded as forbidden. (Cf. ref. [4])).

tary processes are concerned the concept of isobaric parity suffices to rule out undesired interactions †. Of course we cannot speak of spinor or tensor in the isobaric spin space any more, if the full rotational operation is not allowed in this space. In any way we will have to retain at least the rotation around the third axis through an arbitrary angle (this corresponds to the gauge transformation) and the reflection through the 1—2 plane, i.e. the group $C_{\infty h}$.

The author would like to express his thanks to T. Okabayashi who read the manuscript critically. The author has also benefited from conversations with Professor H. Umezawa.

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† In this respect the conservation of the isobaric parity may be seen as an extension of Pais' even-odd rule [5]).

Nuclear Physics, North-Holland Publishing Co., Amsterdam, **1 (1956)**

RELATIVISTIC EFFECTS IN HEAVY NUCLEI

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Received 7 April 1956

Abstract: The binding energy of a model nucleus is discussed in a zero-range scalar field of nuclear forces keeping the relativistic effects in view. According to our results the scalar field free from exchange forces may account for the saturation of the binding energy, in contrast to the conclusions drawn from calculations based on a non-relativistic approach. From the point of view of quantum theory our considerations are of an approximate character; they may, however, serve as evidence for the decisive role which relativistic effects may play in the theory of heavy nuclei.

The conviction that the relativistic effects may play a significant role in the discussion of certain nuclear phenomena has lately gained more and more ground. Attention first centred on the simplest case, the two-nucleon problem. In the quantum theory of the pseudoscalar meson field Lévy pointed out that at small distances the attractive potential may turn into a repulsive potential on relativistic grounds [1]). Starting from the unquantized theory Kunin and Taxar [2]) and, later on, strictly on the basis of classical field theory, Polish and Hungarian physicists [3–9]) tackled the problem in different approximations, considering mainly the behaviour of the two-nucleon potential at small distances.

Much less attention has been paid so far to the relativistic treatment of heavy nuclei. We may refer to the work of G. Szamosi [10]) who, applying the Hartree-Fock method, reduced the many-body problem to a two- and three-body problem and in doing so set up the necessary condition for the saturation of nuclear two- and three-body forces, resulting from the relativistic treatment in a certain approximation.

The obvious reason for treating the heavy nuclei in a non-relativistic way lies in the fact that the approximate methods of quantum theory prove to be rather complicated. In a remarkable paper, however, M. H. Johnson and E. Teller [11]) suggested that the high value of the coupling constant of the π-meson field ($g^2/\hbar c \approx 15$) leads to a high probability of many-meson processes. Consequently

an adequate classical field theory should give an acceptable approximation of the quantized field suitable for treating heavy nuclei. (Another well-known example of this is the possibility of treating the electromagnetic field of alternating currents in a classical way.) The classical potential function φ involved in such a treatment is, of course, indirectly related to the pseudoscalar potential operator of the π-meson field. On this basis Johnson and Teller have worked out a non-relativistic field theory for the heavy nuclei. (From a different starting-point essentially the same conclusions have been drawn by Brueckner [12]) and Eden [13]). The theory of the shell structure of nuclei is also based on the existence of such a potential.)

Assuming the permissibility of a classical field theory approximation, our aim has been to consider the question of the extent to which a non-relativistic approximation is permissible for heavy nuclei, mainly in relation to saturation. In the course of calculations we shall treat all relativistic effects in an exact way, avoiding any approximation. This can only be done, of course, by admitting exceedingly rough approximations in other respects. We, therefore, must not expect from the results obtained precise information on the actual conditions prevailing within the nucleus. What we might expect is that these results indicate, at least in a simple model, the essential and negligible aspects of the relativistic treatment.

As has already been suggested, to describe approximately the field produced by a heavy nucleus we can use a classical potential function φ. In accordance with Johnson and Teller we assume φ to be scalar. The field equations are given directly by the requirements of invariance:

$$\Box\varphi-\mu^2\varphi = 4\pi g\varrho_0 = 4\pi g\varrho\sqrt{1-\beta^2}, \tag{1}$$

where μ and g are constants, ϱ is the density of the nucleons, ϱ_0 the invariant rest density and β the nucleon velocity (measured in units of the velocity of light). Eq. (1) is associated with an expression for the total energy of nucleons and field (cf. ref. [7]))

$$E = \sum_{N=1}^{A}\frac{Mc^2}{\sqrt{1-\beta^2}} + \frac{1}{8\pi}\int\left[(\operatorname{grad}\varphi)^2+\frac{1}{c^2}\left(\frac{\partial\varphi}{\partial t}\right)^2+\mu^2\varphi^2\right]\mathrm{dV}. \tag{2}$$

E, being a constant in time, is to be regarded as the sum of the proper energy of the nucleons and the binding energy of the

nucleus. The proper mass M in (2) cannot be regarded as constant. Due to the covariant equations of motion in a scalar field [4]), M is a function of φ:

$$M = m + \frac{g\varphi(\mathbf{r})}{c^2}, \qquad m = \text{const.} \tag{3}$$

From the solutions of (1) it is clear that μ^{-1} is the range of the nuclear force. Using a finite μ^{-1}, however, calculations carried through in a consistently relativistic way would be rather complicated. For us it will suffice to use only the limits $\mu^{-1} = 0$ and $\mu^{-1} = \infty$. Since the range μ^{-1} appears to be small, rather than large, as compared with the diameter of heavy nuclei, the limit $\mu^{-1} = 0$ is the better approximation. We proceed with our calculations with this limit (Johnson-Teller approximation), using, however, the covariant field equation.

In order to make easier the transition to the limit, we introduce the following quantities:

$$\Phi = -\frac{g\varphi}{mc^2}, \qquad \gamma = \frac{4\pi g^2}{mc^2\mu^2}.$$

Using these symbols and passing to a continuous density distribution we have for the field equation and the energy constant

$$\Phi - \frac{1}{\mu^2}\Box\Phi = \gamma\varrho_0,$$

$$E = mc^2\int\left\{[(1-\Phi(\mathbf{r})]\langle(1-\beta^2)^{-\frac{1}{2}}\rangle\varrho(\mathbf{r})\right.$$
$$\left. + \frac{1}{2\gamma}\left[\Phi(\mathbf{r})^2 + \frac{1}{\mu^2}(\operatorname{grad}\Phi(\mathbf{r}))^2 + \frac{1}{\mu^2 c^2}\left(\frac{\partial\Phi(\mathbf{r})}{\partial t}\right)^2\right]\right\}\,\mathrm{dV}.$$

The average is to be taken, at a given point $(\mathbf{r})$, over the nucleons having different velocities. On going to the limit $\mu^{-1} = 0$ we have to take Φ and γ fixed, since the coupling constant must remain finite:

$$\Phi = \gamma\varrho_0 = \gamma\varrho\sqrt{1-\beta^2}, \tag{4}$$

$$E = mc^2\int\left\{(1-\Phi)\langle(1-\beta^2)^{-\frac{1}{2}}\rangle\varrho + \frac{1}{2\gamma}\Phi^2\right\}\mathrm{dV}. \tag{5}$$

The solution of (4) in the case of a point particle at rest is $\Phi(\mathbf{r}) = \gamma\delta(\mathbf{r}-\mathbf{r}_0)$. Thus we are confronted with the covariant equations of zero range (contact) interaction.

As is well known, nucleons in a nucleus in the ground state are in a stationary but not static state, in which the velocities assume considerable values due mainly to the Pauli principle. The averaging of expressions depending on velocity may be carried out in the simplest way according to the partition function of Fermi-statistics (valid at the absolute zero point). As is well known, for an arbitrary function of the momentum,

$$\langle g(p)\rangle = \frac{1}{N(p_m)}\int_0^{p_m} g(p)\mathrm{d}N(p) = \frac{3}{p_m^3}\int_0^{p_m} g(p)p^2\mathrm{d}p,$$

where (assuming $A = 2Z$)

$$p_m = \frac{h}{2}\left(\frac{3}{2\pi}\right)^{1/3}\varrho^{1/3}.$$

Thus, e.g.,

$$\langle p^2\rangle = \frac{3}{5}p_m^2. \tag{6}$$

We now proceed to average the expression in (5). The momentum of a particle moving in a scalar field [4]) is

$$p = \frac{Mc\beta}{\sqrt{1-\beta^2}} = mc\beta\frac{1-\Phi}{\sqrt{1-\beta^2}}. \tag{7}$$

We introduce the following notation (denoting the radius of the nucleus by $r_0A^{1/3}$):

$$x = \left(\frac{p_m}{Mc}\right)^3 = \frac{3}{16\pi}\left(\frac{h}{mc}\right)^3\frac{\varrho}{(1-\Phi)^3} = \frac{9}{64\pi^2}\left(\frac{h/mc}{r_0}\right)^3(1-\Phi)^{-3}. \tag{8}$$

Thus using (7) we may write

$$\langle(1-\beta^2)^{-1/2}\rangle = \langle(1+p^2/M^2c^2)^{1/2}\rangle = \frac{3}{x}\int_0^{x^{1/3}}\xi^2\sqrt{1+\xi^2}\,\mathrm{d}\xi$$

$$= \frac{3}{8x}\left[(x^{1/3}+2x)\sqrt{1+x^{2/3}} - \log\left(x^{1/3}+\sqrt{1+x^{2/3}}\right)\right] = f(x). \tag{9}$$

Now we recall the energy expression (5). It is a well-known fact that a number of nuclear phenomena can be interpreted with the assumption of $\varrho = \text{const}$. According to field equation (4), in such cases $\Phi = \text{const}$. holds too. Thus the integration in (5) can easily be carried out:

$$\varepsilon \equiv \frac{E}{Amc^2} = (1-\Phi)\langle(1-\beta^2)^{-\frac{1}{2}}\rangle + \frac{\Phi^2}{2\gamma\varrho}.$$

Substituting x for ϱ on the basis of (8) and considering (9), we obtain the following expression for the energy per nucleon:

$$\varepsilon = (1-\Phi)f(x)+\frac{\Phi^2}{2Gx(1-\Phi)^3}, \tag{10}$$

where

$$G=\frac{16\pi}{3}\left(\frac{h}{mc}\right)^{-3}\gamma.$$

In a stationary state, the field equation (4) and the equation determining the density of the nucleus can be obtained by varying (10) with respect to Φ and ϱ respectively. Along with these, however, are two other equivalent equations which are obtained by the variation of ε with respect to Φ and x respectively:

$$\frac{\partial\varepsilon}{\partial\Phi}= -f(x)+\frac{\Phi+\frac{1}{2}\Phi^2}{Gx(1-\Phi)^4}=0, \tag{11}$$

$$\frac{\partial\varepsilon}{\partial x}=(1-\Phi)f'(x)-\frac{\Phi^2}{2Gx^2(1-\Phi)^3}=0. \tag{12}$$

If we determine Φ and x from (11) and (12) and substitute the values obtained into (10), we get the binding energy (the minimum of ε), as a function of the coupling constant G. When Φ and x are known, the density of the nucleus in the equilibrum state is determined from (8).

Actually G is not known, and hence our task is modified as follows. It has to be investigated whether G can be determined such that the binding energy turns out to be in good agreement with experiment and proportional to the atomic weight A. The best way of carrying out the calculations is to eliminate G from (11) and (12) and represent Φ as a function of x (essentially that of equilibrium nucleon density):

$$\Phi(x)=\frac{1-u(x)}{1+u(x)}, \tag{13}$$

where

$$u(x)=\frac{1.5}{x^{2/3}}\left[1-\frac{\log(x^{1/3}+\sqrt{1+x^{2/3}})}{x^{1/3}\sqrt{1+x^{2/3}}}\right]. \tag{14}$$

Eq. (11) determines the relationship between the coupling constant G and the parameter x. Substituting Φ (from (13)) and G (from (11)) into (10), we have the following expression for the nuclear energy per nucleon:

$$\varepsilon_{\min} = (1-\Phi(x))\sqrt{1+x^{2/3}}. \tag{15}$$

We note that the energy per nucleon, as well as the nuclear density from (8) have turned out to be finite constants independent of the atomic weight A. Thus it is obvious that the scalar field might be able to provide the saturation of the nucleus. This is due solely to the relativistic treatment, as it is a well-known fact that common Wigner forces arising out of the scalar field in a non relativistic approximation would lead to the collapse of the nucleus, to a binding energy proportional to A^2, and to a small nuclear radius independent of A. For in a non relativistic approach eq. (6) can be written

$$E-Amc^2 = mc^2 \int \left[\frac{1}{2}\langle\beta^2\rangle\varrho-\varrho\Phi+\frac{\Phi^2}{2\gamma}\right] \mathrm{dV}$$

$$= mc^2 \int \left[\frac{3}{40}\left(\frac{3}{2\pi}\right)^{2/3}\frac{h^2}{m^2c^2}\varrho^{2/3}-\varrho\Phi+\frac{\Phi^2}{2\gamma}\right] \mathrm{dV}.$$

Evaluating the integral for $\varrho = \text{const.}$, $\Phi = \text{const.}$ we get

$$\varepsilon-1 = \frac{3}{40}\left(\frac{3}{2\pi}\right)^{2/3}\frac{h^2}{m^2c^2}\varrho^{2/3}-\Phi+\frac{\Phi^2}{2\gamma\varrho}.$$

Differentiating with respect to Φ we have the non relativistic form of (4):

$$\Phi = \gamma\varrho.$$

Substituting this back, the binding energy per particle, as a function of the nuclear density, is given by

$$\varepsilon-1 = \frac{3}{40}\left(\frac{3}{2\pi}\right)^{2/3}\frac{h^2}{m^2c^2}\varrho^{2/3}-\frac{1}{2}\gamma\varrho.$$

This expression has its minimum for $\varrho = \infty$, that is to say, in the perfectly collapsed state of the nucleus. In the relativistic treatment the potential dependence of the proper mass and the factor $\sqrt{1-\beta^2}$ in the field equation and energy introduce a non-linearity into the field and state equations, such as to lead to an energy minimum even at finite values of Φ and ϱ.

Using concrete data, we may now evaluate the quantities occurring in our equations. As is well known, if in the semi-empirical formula for the binding energy of the nucleus, we neglect the "surface energy" term proportional to $A^{2/3}$ (which appears as a consequence of the finite range of nuclear forces) as well as the Coulomb energy and some other correction terms of minor im-

portance, an expression proportional to the atomic weight A remains. The coefficient of A, i.e. the binding energy per nucleon, is 15 MeV, thus the empirical value of $\varepsilon_{\min}$ is about 0.985. A simple calculation making use of (15) shows that with $x \approx 3$, $\varepsilon_{\min}$ does take up that value. (According to (11) a coupling constant $G \approx 0.77$ leads to the value $x \approx 3$.)

Let us now consider the values of some other physical data of the nucleus. First, we have the value of $\Phi = 0.44$, which means that the potential energy within the nucleus has, according to our model, the value $V = -mc^2\Phi = -400$ MeV. This high potential, owing to the scalar character of the field, results, according to (3), in the proper mass of the nucleons in the nucleus amounting to no more than 56 per cent of their free mass †. The density of the nucleus, i.e. the nuclear radius which is closely related to it, can also be determined by (8). Substituting the already known value of x, a value is obtained which is one third of the empirical value. This result shows that our highly simplified model is not suitable to produce correct values for the nucleus, as has already been emphasized in the introduction. However, it does help us to obtain information on the role of relativistic effects. The occurrence of saturation is obviously not affected by the range μ^{-1} being different from zero, the Coulomb repulsion and the corrections occurring in the kinetic energy in quantum mechanics; but the values for the density of the nucleus, on the other hand, may be altered by them. (According to our formulas the nuclear radius is rather highly dependent on the choice of the coupling constant G, whereas the value of x is much less so. The saturation occurs also in the case of coupling constants giving more reasonable values for the nuclear radius. The particle energy remains significantly negative here too, but the positive field energy raises the total energy considerably above the empirical values of the energy of nuclei.)

The amount of the energy of the nucleons in the nucleus is given by the product of their inert mass $\mathcal{M}$ and c^2:

$$E_{\text{particle}} = \sum_{N=1}^{A} \mathcal{M}_N c^2 = A \langle \mathcal{M} \rangle c^2 = 0.83\, A\, mc^2 \quad (\mathcal{M} = M/\sqrt{1-\beta^2}).$$

† In different ways, similar conclusions have been drawn by Brueckner[12]) and Johnson and Teller[11]). As was shown by Rand[14]), the decrease of the nucleon masses within the nucleus is a suitable explanation for the unexplained theoretical implications of the "giant resonance" of the nuclear photoeffect. Another effect of the same kind is the increase of the e/M value of nucleons in the nucleus, which influences the cross sections of the nuclear photoeffect.

This, however, differs considerably from the total energy following from mass defect measurements; for, as the last term of (5), the field energy (which is always positive on account of the nucleon charges having the same sign) is added to the particle energy. From this we can conclude that from the smallness of the proportion of binding energy to proper energy ($1-\varepsilon = 0.015$), it does not follow that the motion of the particles in the nucleus is non relativistic; for only the sum of the particle and field energies agrees, within 1.5 per cent, with the proper energy. The deviation of the particle energy from the proper one varies in our model between $-44\,\%$ and $-1.5\,\%$. (It is of interest to point out that the form of the total binding energy of the nucleus, according to (15), is as if all the nucleons moved with the maximum velocity prescribed by the Fermi statistics and the field energy were zero.)

In order to avoid all the difficulties arising from the exact averaging of the expression $(1-\beta^2)^{-\frac{1}{2}}$, it is worth considering whether we cannot employ in the relativistic calculation such an approximation that would make possible greater accuracy, e.g. in the field of quantal effects.

A rough approximation, which can give information about the order of magnitude, is

$$\langle(1-\beta^2)^{-\frac{1}{2}}\rangle = 1+\tfrac{1}{2}\langle\beta^2\rangle + \ldots = 1+0.3\,x^{\frac{2}{3}}+\ldots$$

In this case (10) assumes the simple form

$$\varepsilon-1 = \frac{3}{40}\left(\frac{3}{2\pi}\right)^{\frac{2}{3}}\frac{h^2}{m^2c^2}\frac{\varrho^{\frac{2}{3}}}{1-\Phi}-\Phi+\frac{\Phi^2}{2\gamma\varrho}.$$

Let us compare this expression with that used by Johnson and Teller in the paper referred to above,

$$\varepsilon-1 = \frac{3}{40}\left(\frac{3}{2\pi}\right)^{\frac{2}{3}}\frac{h^2}{m^2c^2}\varrho^{\frac{2}{3}}(1+F\Phi)-\Phi+\frac{\Phi^2}{2\gamma\varrho}.$$

We see that the density and velocity dependence of the two energy formulas agree, which makes it easy to understand that the saturation of the nuclei can be explained by both equations. The Johnson-Teller energy differs from the one used here only in that it uses the non-relativistic kinetic energy and, assuming a further interaction depending on velocity, takes as the proper mass $m(1+F\Phi)^{-1}$ instead of $m(1-\Phi)$ given directly by the scalar field. (Thus, another arbitrary constant F appears, which, by adequate choice, makes it possible to fit the nuclear density to experiment.) We see,

therefore, that the relativistic calculation forms the theoretical basis, in a certain sense, of the assumption made by Johnson and Teller.

We conclude our paper by giving a summary of our calculations. In a simplified model of the nucleus we have considered the role of the relativistic effects. According to the calculations the saturation of the binding energy can be obtained by a scalar field, which, in a non relativistic approxmation, would lead to the collapse of the nucleus. The relativistic effects may counterbalance the collapse-producing character of the Wigner forces, originating from the scalar field, in two ways. On the one hand by the decrease of the proper mass, according to (3), even with a given momentum distribution fixed by the Fermi statistics, an increased velocity and kinetic energy is produced. On the other hand, the nucleon velocities result, in the sense of field equations (1) and (4), respectively, in the moving nucleons producing a weaker field than would be obtained with a statistic approximation. Our model — in consequence of its neglecting quantal effects and using an oversimplified law of interaction — is inappropriate for giving correct numerical values of several nuclear data. One can hope the full explanation of the chief characteristics of nuclei might be founded on a theory which deduces the classical potential from the quantum theory of meson fields (according to the ideas of Johnson-Teller or Brueckner-Eden), but without the complete neglect of all relativistic effects characteristic of heavy nuclei. It is possible that one can derive from an averaging of certain quantal quantities (spin etc.), the two different "effective" coupling constants F and G postulated by Johnson and Teller.

I am indebted to Dr. G. Szamosi (Budapest) and Dr. J. Plebanski (Warsaw) for most valuable discussions which helped me greatly in clearing up the problems discussed.

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BOOK REVIEWS

S. S. SCHWEBER, H. A. BETHE, F. DE HOFFMANN, *Mesons and fields*, Vol. I (Fields) (Row, Peterson & Co, Evanston 1955. viii-449 pages, $ 8; $ 15 for the two vols.).

The first volume of this important work has now been issued only a few months after the second, thus providing the physicists who are engaged in research on this fundamental subject with an indispensable reference work. The present volume exhibits the same general characteristics as the other, which was reviewed in this journal (Nuc. Phys. **1** (1956) 229), except of course that it is entirely theoretical in content and outlook. Like his great teacher Sommerfeld, Prof. Bethe is more concerned to write about the practical methods leading to concrete results than about the more abstract problems raised by the efforts to establish field theory on firm foundations. He has therefore chosen to confine himself to the original Feynman-Dyson formulation of the theory which is usually the most helpful in the actual carrying out of calculations; and his account of it is indeed of admirable precision and clarity. The other approaches to the difficult problems of renormalisation and consistency, on the other hand, are only mentioned in a casual and sketchy manner, which too often fails to do justice to their merits; the reader is just faced with a mass of references to papers for the study of which the text does not provide a sufficiently clear and reliable guidance. It must be said, regretfully, that in this respect the book is most disappointing.

L. R.

A. EINSTEIN, *The meaning of relativity*, Fifth Edition (Princeton University Press, Princeton N. J. 1955. 166 pages, $ 3.75).

A new edition of a well-known classic. The Appendix II, containing Einstein's last attempt at a unified theory, is given in a new version, which presents interesting considerations on the general character of field theories.

L. R.

M. G. MAYER and J. H. D. JENSEN, *Elementary theory of nuclear shell structure* (John Wiley & Sons, New York — Chapman & Hall, London, 1955. xiv-269 pages, 62 s.)

The two physicists who independently recognised the importance of spin-orbit coupling in characterising the individual nucleon states, and thus for the first time devised a workable shell model of nuclear structure, have joined forces to survey the rich field opened up by their discovery. The well-coordinated picture of nuclear properties afforded by the model is made up of data supplied by highly specialised experimental investigations of the most varied nature. It has therefore been for some time a compelling task to present the fundamental features of the model and a comprehensive summary of the results hitherto achieved in a fashion palatable to the experimental physicists (who, as is well-known, affect to find mathematical arguments difficult to follow). Several excellent survey articles have already appeared in response to this need, but the present book, with its larger scope and fuller treatment, will be welcomed, not only as a serviceable guide to those already engaged in research in this vast field, but more generally as an authoritative introduction into it for those who wish to acquaint themselves with one of the chief problems of nuclear physics. Even the more theoretically minded will find the book extremely helpful; after all, the theoretical techniques which are not treated in it are of a straightforward kind and can easily be looked up in the original papers

if need be (I am not speaking, of course, of the symplectic group, the mysteries of which require an exclusive initiation anyhow!)

The general set-up of the book follows a straightforward plan and covers the whole ground extensively. The exposition is clear and concise, and well illustrated by examples and diagrams. The latter are mostly familiar from the published papers, which does not mean that they always provide the best representation of the point at issue. There is a full tabular presentation of the relevant data, which is most useful; the inclusion of a few more graphs, however, would have enhanced still more the practical usefulness of the book. Excellent appendices offer in a nutshell the main theoretical concepts and formulae, most conveniently collected for direct application.

If we now scrutinise the detailed treatment of the various aspects of the subject, we do not find everywhere, unfortunately, the same degree of excellence. What the authors sometimes lack is certainly not competence or critical judgment, but simply sufficient information about the work of others. They themselves confess, in the preface, to an 'arbitrary selection' in this respect, and somewhat lightheartedly afford as an excuse their aim of writing an introduction and not an 'exhaustive compilation'. This would be all right if they did not too often ignore contributions of really significant value to the very argument they present. This is not the result of carefully considered restraint, but of sheer negligence. It is small consolation to observe that such neglect of foreign work is an attitude not confined to our authors, but widespread among American physicists. The chaotic conditions of publication outside the United States have no doubt something to do with this deplorable state of affairs. Is it too much to hope that *Nuclear Physics* might help to restore some balance in the appreciation and utilisation of valuable contributions to the common endeavour by making them more easily accessible?

L. R.

A. S. THOMPSON and O. E. RODGERS, *Thermal power from nuclear reactors* (John Wiley & Sons, New York – Chapman & Hall, London, 1956. xiii-229 pages, $ 7.25, 58 s.)

The authors suggest in their preface that this book will cover "methods of handling design problems" and we are told on the flyleaf that it will "fill the need of men with engineering backgrounds as a guide in reactor design". Such a need undeniably exists, but unfortunately the present work leaves it largely unfilled, owing to the superficial treatment given to many parts of the subject matter.

The field covered has been chosen to be of interest to mechanical engineers. The first chapter contains a sketchy, but readable introduction to nuclear reactor theory and is followed by a second chapter (probably the best in the book), on critical size calculations, into which dimensional analysis and numerical techniques are introduced. But in this chapter, as in the book as a whole, the treatment of each topic is all beginning and no end – the reader's attention is held at first by what appears to be an interesting discussion which eventually peters out inconclusively.

General outlines of reactor kinetics and shielding follow in the next two chapters and contain some quantitative analysis which infers a simplicity that the problems do not in fact possess.

Short, readable surveys of reactor materials and thermal stress calculations are followed by a chapter on power extraction, wherein heat transfer analysis is treated with a perfunctoriness quite out of place in a book of this kind. In the final chapter on thermal power cycles some material on cycle efficiencies, familiar to every mechanical engineering student, is presented in such a way that a reader not so familiar with the subject matter could easily be misled as to the origin of certain

thermodynamic fundamentals. These last two chapters contain very little direct application of the elementary theory described to nuclear engineering problems. There is no discussion, for example, of thermal cycles of direct interest to nuclear engineers, such as multi-pressure steam cycles.

It is difficult to visualise a group of readers to whom this book would be of particular value. Mechanical engineers interested in reactor design require a considerably more detailed treatment, and would already be familiar (or should be) with the elementary treatment of fundamentals to which about half the book is devoted. It may be of passing interest to undergraduates who intend to enter the nuclear engineering field, but at 58/- a copy they would not be likely to regard it as a good investment. The scarcity of numerical data and worked design examples does not add to the book's value and, apart from a few foot-notes, no attempt is made to give numbered references or to produce a reasonably comprehensive bibliography for further reading.

J. Diamond

U.S. Atomic Energy Commission, *Selected reference material on atomic energy* (6 volumes) (McGraw-Hill Book Co, New York, Toronto, London, 1955).

Research Reactors (460 pages, 49 s.).

This book contains a detailed description of six types of research reactors which have been built in the United States. These are thermal reactors and can be classified according to the type of moderator and fuel, and the arrangement of the moderator and fuel in the core. The power generated by the smallest reactor is a watt and the largest generates 30 MW, with maximum fluxes of neutrons of about 2.10^{14}n/cm^2/sec, so that quite a range of types is considered.

Three reactors use enriched fuel and light water as a moderator. The water boiler reactor has a core consisting of a homogeneous mixture of uranium enriched in the 235 isotope and light water. The other two reactors have a heterogeneous core, one is the so called "swimming pool" type of reactor used for neutron shielding studies and the other is a materials testing reactor. A vast amount of information is given about these two reactors, in fact one half of the book is devoted to them. A similar type of reactor is also described using oil as a moderator. The fifth type uses heavy water as a moderator and enriched uranium as a fuel. The last type to be described is a reactor using natural uranium as a fuel and graphite as a moderator and air cooling.

The book is divided into a number of chapters giving the technical data on each reactor. There is a short four page introduction describing the uses of the reactors for physics, biomedical and industrial research and also estimates of performance and costs. The reasons for building a given type of reactor are given in the chapter describing the reactor. For example, a brief design history of the materials testing reactor is given on p. 161; the reasons are given why a light water moderated reactor was chosen instead of a heavy water moderated type. The reasons given are convincing when small scale experiments are being considered; however, it is a debatable point whether or not this type of reactor is the best for large scale experiments. On reading the chapter on the bulk shielding reactor, it is obvious that this is an ideal reactor as it has a low cost and is very flexible.

This book should be welcomed as it contains such a large amount of useful technical information.

J. H. Tait

Reactor Handbook, Vol. 1: Physics (790 pages, $ 12, 90 s.).

This volume is a compilation of data and formulae of those parts of physics, mainly nuclear, which find application in the technology of reactors. The first section (616 pages) covers properties of atomic nuclei, presented mainly in the form of tables and graphs; kinetics of neutrons; reactor statics and dynamics, again chiefly graphs. The second section is devoted to radiation shielding. Such a book has no scientific interest, but is merely in the nature of a handy compendium. It has also full lists of references; two appendices giving conversion factors and units, and basic data concerning some types of reactors; and an index. L. R.

Reactor Handbook, Vol. 2: Engineering (1088 pages, £ 5.12.6).

A few interesting chapters mixed in with a vast mass of conventional engineering data and information, most of which has been adequately dealt with elsewhere. The balance of this handbook probably reflects the U.S.A.E.C. reactor research programme since fully 25 % of its contents are devoted to various types of homogeneous systems, whereas gas cooled systems of the greatest interest to United Kingdom engineers are summarily dismissed in a small inadequate chapter.

The handbook is divided up into sections dealing with the various reactor types, light and heavy water, liquid metal and gas cooled heterogeneous systems, homogeneous reactors based on liquid metal aqueous solutions and fused salts followed by subsidiary sections on active handling and control. A final chapter describes briefly constructional details of a number of U.S.A. reactor experiments.

This handbook is unlikely to attract the discriminating engineer. H. J. Grout

Reactor Handbook, Vol. 3: Materials (614 pages, 79 s.).

This Handbook was first issued by the U.S. Atomic Energy Commission in 1952; the present declassified edition was prepared for the Geneva Conference. It describes the preparation, fabrication and physical properties of over twenty metals and ceramics used by scientists and engineers in atomic energy. The subject matter has not been revised since August 1952, and has been drawn mainly from U.S. sources.

The eminence of those who have helped on the individual chapters inspires confidence in the data, but cannot altogether compensate for the scarcity of references. Although many of the material have been dealt with more extensively in other books, this Handbook supplies a very useful compilation.

J. A. L. Robertson

Neutron Cross-sections (328 pages, $ 12).

This most useful and serviceable compilation of data on cross-sections for absorption and scattering of neutrons by nuclei is the work of D. J. Hughes and J. A. Harvey, of the Brookhaven National Laboratory, whose important contributions to this field are well-known.

The book is an album (39×25 cm) consisting mainly of graphs giving cross-sections in terms of energy for the various elements. The arrangement of these graphs is as well thought out as one can wish to supply at a glance the fullest available information. Whenever possible, capture or fission cross-sections are given separately.

The graphs are preceded by 53 pages of tabulated material and references about thermal cross-sections and resonance parameters. They are followed by a full list of resonances and a series of smaller graphs of angular distributions for elastic scattering.

The typographical execution, which must have presented no small problem, deserves the highest praise. L. R.

Chemical Processing and Equipment (xii—302 pages, 45 s.).

The first part of this book describes a chemical processing plant at Idaho, which recovers fissile material etc. from reactor fuel elements; this is a particular plant for the processing of various test and experimental reactors in the U.S.A. There is an account of the facilities, equipment, and process provided for uranium recovery from enriched uranium-aluminium fuels; the equipment described is adaptable to the processing of other types of fuels. The plant is the first A.E.C. processing facility designed for direct rather than remote maintenance. There is a good description of the procedures for plant decontamination which is a necessity for the successful operation of this type of maintenance. The operations of fuel alloy dissolution; extraction and back-extraction of uranium nitrate from the feed solution using methyl *iso*-butyl ketone (hexone); product and waste handling; and solvent recovery are described with the aid of block diagrams and flow sheets. In addition, the geographical and architectural layout of the plant, special and mechanical equipment, instrumentation, analytical and health physics control, and the relative proportions of different costs are included.

The remainder (80 %) of the book is devoted to a description of many items of apparatus and equipment which have been developed for special uses in laboratories handling highly radioactive materials. Remote handling methods of performing common operations are well to the fore.

This volume will be of particular value to chemists and chemical engineers concerned with the design and provision of research and development facilities for radiochemical operations connected with isotopic production or nuclear power reactors.

J. M. Fletcher
F. S. Martin

J. M. JAUCH and F. ROHRLICH, *The theory of photons and electrons* (Addison-Wesley Publishing Co., Cambridge, Mass. 1955. xiv-488 pages, $ 10)

This book contains a detailed account of the principles, methods and applications of quantum electrodynamics. It is not necessary to enumerate the topics discussed or to describe the plan according to which they are presented. These features are in fact so straightforward that — apart from some variations and shifts of emphasis — they are found to be common to the rapidly increasing number of treatises on quantum field theory which are being produced in response to an obvious need. What distinguishes the present volume is the uncommonly neat and painstaking treatment of details. One must be thankful to the authors for the considerable work they have devoted to the elucidation of every possible difficulty (in which, as is well-known, the subject abounds), and they must be congratulated for a most successful accomplishment of this task. They have given us an exposition of the subject which is so sound, critical and elegant as to provide an excellent advanced textbook, and sufficiently complete — thanks to an extensive, but very critical, use of the published papers — to serve as a reliable guide to which workers in the field will profitably resort. It is a specially commendable feature of the authors' effort to provide their fellow-workers with a serviceable tool that they have not shrunk from pointing to shortcomings in some published papers. The typographical production of the book is, as usual with the specialised American publishers, of the highest standard.

I should not like to end this review without finding *some* fault with the book. Its weak point is the almost complete absence of any discussion of the physical foundations of the theory. I am not so much blaming the authors for having shunned the examination of the consistency problem; one may regret, but understand, the

decision to omit it. What I find unforgivable, however, is that they do not even make any mention of the correspondence argument. This argument is not merely of historical or 'philosophical' significance. In the present case, it would throw light, for instance, on the physical meaning of the authors' purely formal treatment of the Coulomb field and of the external fields.

L. R.

E. R. ANDREW, *Nuclear magnetic resonance* (Cambridge University Press, 1955. xi+265 pages, 35 s.)

Nuclear resonance is of importance in several branches of physics and chemistry. For the nuclear physicist its interest lies in the very precise determination of nuclear magnetic moments which it yields. The solid state physicist sees in it a tool to explore the regularity and irregularity of the crystalline state. The organic chemist can use it to discriminate between models of molecular structure.

Professor Andrew's book gives a very clear account of these, and other aspects of nuclear resonance. It starts with a lucid exposition of the basic theory, followed by an ample survey of experimental methods. Separate chapters are then devoted to nuclear measurements, to nuclear resonance in liquids and gases, in non-metallic solids, and in metals. A final chapter is concerned with quadrupole effects.

The exposition is everywhere straightforward and easy to follow, yet the author has managed to convey an enormous amount of factual information. It should prove a very useful book to students and to research workers in the field.

M. H. L. Pryce

NEWS ITEMS

UNITED INSTITUTE OF NUCLEAR PROBLEMS

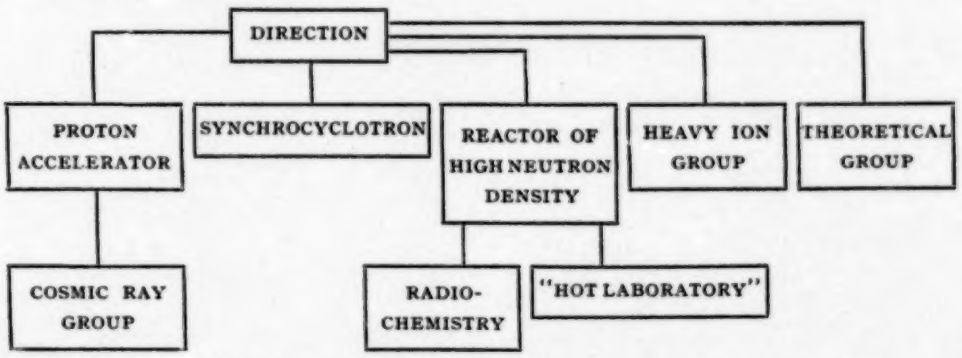
In 1949 an Institute of Nuclear Problems was established by the Academy of Sciences of the Soviet Union on a site not far from the junction of the Moskva-Volga canal with the river Volga, about 150 km from Moscow. On this site laboratories and accessory plants were installed to operate a 680 MeV synchrocyclotron and a 10 GeV proton accelerator ("synchrophasotron").

These installations form the nucleus of a new city, providing the personnel and their families with urban accomodation and facilities in pleasantly wooded surroundings.

The equipment of the Institute is going to be considerably increased, in particular by the adjunction of a reactor of high neutron density with accessory laboratories. Without waiting for the completion of this expansion, however, it has recently been decided to transform this admirable research centre into a United Institute of Nuclear Problems which will be put at the disposal of the physicists of a number of countries sharing its administration. At the moment these countries are, beside the Soviet Union, Albania, Bulgaria, China, Corea, Czechoslovakia, the Democratic German Republic, Hungary, Mongolia, Poland and Rumania. Statutes are being elaborated for the running of the new Institute, and in particular arrangements are being contemplated to enable guests from other countries as well to avail themselves of its facilities.

The direction of the United Institute is shared by the participating countries. The director, D. Blokhintzev (U.S.S.R.) is assisted by two deputy-directors, M. Danysz (Poland) and V. Votruba (Czechoslovakia).

The Institute, when completed, will be divided into various research groups according to the following scheme:



The heads of the already existing groups are:

proton accelerator: V. J. Veksler,
synchrocyclotron: M. G. Meschеryakov,
theoretical group: M. A. Markov.

A summary description will now be given of the two large accelerators of the Institute.

1. The 680 MeV proton synchrocyclotron

The poles of the electromagnet are of 6000 mm diameter. The magnet gap is 600 mm wide. The magnetic field intensity in the gap is equal to 16800 Oe. Because of the 5 % decrease of the field intensity at the magnet edge the focusing is quite strong.

After extensive experimental work the radius of magnetic field used was raised to 2780 mm; the particle orbit was brought to the median plane. This work was preceded by the development of new types of magnetometric instruments of high sensitivity.

The easily demountable brass vacuum chamber has rubber tape packings. The bottom and the cover plates of the chamber are adjusted to the poles and are packed by means of rubber rings. The chamber volume is of the order of 30 m^3. It is evacuated by two high vacuum pumps with total pumping speed of 30000 l/sec. The pressure in the chamber during the operation is 6×10^{-6} mm Hg. The limiting pressure in the chamber is equal to $1—2 \times 10^{-6}$ mm Hg if the H_2-inlet in the ion source is stopped.

In contrast to usual proton synchrocyclotrons, the r.f. accelerating field between the edge of the dee and the grounded frame is obtained by means of half wave systems: dee resonance line frequency variator. The accelerating field frequency is varied from 26 to 13 Mc as the variator rotates. Some design peculiarities of the resonance line in the frequency variator permit to diminish considerably the r.f. currents through the variator bearings. The synchrocyclotron operation demonstrated the reliability and the stability of the r.f. system design. The aggregates of r.f. system can work for thousands of hours without repair.

The synchrocyclotron equipment permits to turn out the r. f. supply during the idle part of the cycle, to obtain single accelerating cycles, to control the pulsed voltage of the ion-source and to switch on the desired nuclear research instruments and assemblies mounted along the external particle beams. All these processes are linked to the frequency change cycle of the main r.f. oscillator by means of a special system. The r. f. voltage switch on is accomplished by a photoelectric system before the cycle begins. The light beam falling upon a photoelectric multiplier is interrupted by the variator rotor vanes.

The total accelerator aggregate control, the high and forvacuum pumps and refrigerating machines included, is accomplished automatically from a special building at 400 m from the synchrocyclotron. All the supply and refrigerating aggregates are mounted in this building. So is the check and control equipment of those aggregates which must be mounted in the close vicinity of the accelerator.

The electromagnet and the vacuum chamber are located in a large room, where a part of the physical research equipment is also installed. Thus the accelerator operation and the internal targets management is greatly simplified and the possibility is acquired to use a great number of external particle beams, as described below. The main equipment is located behind a 6 m thick concrete shield. A new system permits to eject from the vacuum chamber 7 % of accelerated protons.

The following investigations are carried out on the synchrocyclotron:

a) elastic proton – proton, neutron – neutron and neutron – proton scattering,

b) neutral and charged pion production in nucleon – nucleon and nucleon – deuteron collisions,

c) pion – nucleon interactions.

The design of the synchrocyclotron gives the possibility of obtaining a great number of different high energy particle beams emerging from any desired point of the accelerated proton orbit and consequently a high utilization of the accelerator. In the shield of the six-meter synchrocyclotron there are sixteen collimators which are used to obtain beams of unpolarized and polarized nucleons, of charged pions and also beams of gamma-rays from neutral pion decay. The collimators are placed not only in the main concrete shield but also in the synchrocyclotron magnet yoke, which in this way is used as a radiation shield.

The accelerator chamber is supplied with four probes with the help of which it is possible to introduce in the camera samples of various substances. These can be

irradiated in the internal proton beam at any desired energy up to 680 MeV. The overall shielding and collimation system is designed in such a way as to widely utilize the possibility of simultaneous carrying out of many experiments on various particle beams used in "parallel" work, either of the same kind as, for example, in the case of mesons with different energies, or of different kinds, as in the case of neutrons and polarized proton beams.

For the purpose of increasing the synchrocyclotron utilization wide use is made of automatic and remote control of equipment located in rooms where, for biological reasons, human beings are not allowed to stay when the accelerator is working. For the same purpose multi-channel electronic systems for registration of nuclear processes are widely used.

2. The 10 GeV proton accelerator

The 10 GeV proton synchrocyclotron is built to study the nature of the nuclear forces, the properties of mesons, of hyperons and of antiprotons, the nuclear cascades and so on. It is so far the most powerful accelerator of this type.

Principal characteristics of the accelerator:

Maximum particle energy	10 GeV
Energy of injection	7.5 MeV
Orbit radius	28 m
Number of straight sections	4
Length of a straight section	8 m
Electromagnet weight	35000 tons
Duration of the accelerating cycle	3.3 sec
Number of cycles per minute	5
Inner dimensions of the vacuum chamber	0.4×2.0 m^2
Maximum field strength in the gap	13 000 Oe
Operation pressure in the chamber	$2—3 \times 10^{-6}$ mm Hg
Intensity of the accelerated particle beam	$10^9—10^{10}$ particles in a pulse

Injection of particles into the chamber is carried out by means of a system consisting of a 570 keV forinjector, a 7.5 MeV linear accelerator and an ion optic arrangement which includes beam focusing and position correcting units as well as of an electromagnet and ajusting capacitors guiding the beam and fitting it to the orbit with an angular precision of 3.

The electromagnet having a H-shape consists of 48 demontable blocks assembled of steel plates 10 to 40 mm thick. The electromagnet coil is supplied by 11 kV voltage pulses; maximum coil current is about 13 000 A. The coil is cooled by water.

The vacuum chamber has double walls. Pressure of the order of 1 mm Hg is maintained in the fore vacuum chamber. The high-vacuum chamber is built of thin stainless steel sheets; the junctions between the sheets are packed by means of a special rubber. The operating zone extension coils as well as the inductance coil of the integrating field measurer and some other devices are placed on the upper and on the lower wallsides of the chamber.

The high-vacuum chamber is evacuated by 56 5000 l/sec high-vacuum pumps. The liquid nitrogen supply of pump to traps to freeze out the oil vapours is accomplished by means of a tube system with vacuum heat isolation. The vacuum system valves have pneumo-hydraulic remote control.

The electromagnet supply is accomplished by 4 chains of ignitron transformers, 24 ignitrons each, fed by a.c. generators with a nominal power of about 150 000 kWA.

The generators are supplied with heavy flywheels to store the energy during the ignitron transformer inversion cycle.

The acceleration is accomplished in two straight sections by means of 7 m long electrodes. The frequency of 20 kV supply of the electrodes varies from 0.18 to 1.45 Mc depending on the magnetic field. To tune the output cascades the permeability of the ferrite cores of inductance coils is automatically changed by means of direct current.

A system of linkage between the frequency of the r.f. accelerating field and the magnetic field intensity H ensures the necessary dependence $f(H)$ with 0.1% accuracy.

To control the processes of injection and of acceleration a special system was developed forming the control pulses related to the magnetic field intensity with 4×10^{-3} accuracy.

A special precision measuring equipment accomplished the measurement of instantaneous values of accelerating field frequency with 5×10^{-4} accuracy, of magnetic field intensity with 10^{-3} accuracy, etc.

The electromagnet with the vacuum chamber and equipment which must be located in the close proximity of the chamber (injector, vacuum pumping system, output r.f. cascades and so on) are situated in a special building. An experimental installation building is situated nearby behind a 8 m concrete shielding.

All the other elements of the accelerator — the electromagnet supply system, the electronics, the aperiodical r.f. amplifiers etc. — are located in another building situated 100 m from the first; in the same building the principal control panel of remote control of all the accelerator systems is situated.

THE MOSCOW CONFERENCE ON THE PHYSICS OF PARTICLES OF HIGH ENERGY (14—22 MAY 1956)

An All-Union Conference on the physics of particles of high energy, organized by the Academy of Sciences of the U.S.S.R., was held in Moscow from the 14th to the 22nd May, 1956. The conference was attended by about a thousand Soviet physicists and about 60 foreign guests (including about 15 from the people's democracies, 14 from the United States and smaller groups from most European countries, Australia and Canada). The conference was divided into three sections, whose sessions mostly overlapped: (a) elementary particles and their interactions (96 scheduled communications), (b) high-energy accelerators of elementary particles (79 communications), (c) theoretical investigations on high-energy physics (25 communications). Meetings were held almost every day in the morning and the late afternoon and were often prolonged, with unrelenting energy, for an indefinite time. Additional informal meetings were held by the theoretical physicists. Discussions were most stimulating and at times very lively, especially those of the Soviet physicists among themselves.

Altogether, the contacts, scientific and other, between the foreign physicists and their hosts were marked by great cordiality. The foreign guests, received with overwhelming hospitality, had ample opportunity of visiting various laboratories and institutions both in and around Moscow and at Leningrad and Kiev. Particularly impressive was the inspection of the Institute of Nuclear Problems on the river Volga.

In section (a), many new experimental data and some theoretical considerations were presented, bearing on the interactions between nucleons, π-mesons and nuclei; especially scattering processes, meson production, antiproton production and annihilation, photonuclear reactions were extensively discussed. Besides, heavy mesons and hyperons received due attention.

In section (c), there was a great variety of topics to which the Soviet groups made important and highly original contributions. L. D. Landau and his collaborators, especially I. Y. Pomeranchuk, developed with great vigour their arguments tending to establish the inconsistency of the present form of quantum field theory. Other groups presented new developments of the dispersion relations and of various aspects of meson theory.

Section (b), although mainly concerned with technical problems, had to consider also interesting questions of a more fundamental nature, connected with the stability of particle orbits in the accelerators. In the opening session were presented not only descriptions of the large accelerators already completed in the Soviet Union, but also accounts of projected proton accelerators of still larger energies: the 15 GeV proton synchroton of Argonne National Laboratory and the U.S.S.R. Academy of Sciences strong focusing 50—60 GeV proton accelerator, with the accompanying study of a 6—7 GeV accelerator on the same principle. Here is a summary account of the Soviet project, according to V. V. Vladimirsky, E. G. Komar and A. L. Minz.

Project of a ring proton accelerator for 6—7 GeV

The main parameters of the accelerator are the following:

Maximum accelerated particles energy	7 GeV
Injection energy	4 MeV
Mean orbit radius	40 m
Number of magnets	112
Number of compensating magnets	14
Number of radial and vertical oscillations per revolution	12.75
Chamber width	11 cm
Chamber height	8 cm
Magnetic system weight	2700 tons
Magnetic field energy stock	10^7 joule

In the project a system of compensating the length of the orbit with rise of particle momentum is adopted. The use of compensating magnets has somewhat increased the mean accelerator radius, but led to some allay of tolerances. In the compensating magnet are placed the span tubes of the accelerating system working on the 7th harmonics of the revolution frequency. The vacuum chamber is a thin-walled (0.2 mm) corrugated tube of oval section made of stainless steel. 16 compensating magnets have a X-shape type yoke, the other magnets are of C-shape type with a separate neutral pole. The foundation of the magnet system is a massive solid concrete ring. It has a sufficient rigidity to suppress all dangerous harmonical displacements of the accelerator arising from irregular ground settling.

The main characteristics of the projected strong focusing 50—60 GeV proton accelerator

In performing the project of the 50—60 GeV proton-accelerator the variant with the elimination of the critical energy by introduction into the magnetic system of compensating magnets with inverse magnetic field was chosen. The magnetic system of the accelerator will consist of 105 guiding-field magnets with alternating radial and vertical focusing, and of 15 compensating magnets. Each eighth magnet will be a compensating one. The length of the orbit will be 1480 m, the initial field-intensity at the injection will be 90 Oe, the maximum field-intensity will reach 10.000—12.000 Oe. The weight of the iron in the yokes will reach about 17 thousand tons; the whole weight of the magnets, including design-elements of the magnets, will be about 22 thousand tons. The main characteristics of the orbit, the tolerances of the magnetic field distribution and of the momentum value and the characteristics of the power-supply of the accelerator are listed below.

A 10^8 eV linear accelerator will serve as the injector device. The accelerating system will be supplied with high-frequency power at a frequency 30 times the revolution frequency of the particles.

The energy the protons get during one revolution will amount to about 10^5 eV. Transformers with ferrite cores will be used as accelerating units. The power of the high-frequency oscillators will be about 500 kW. The main parameters of the high-frequency system are given below.

1. *The main parameters of the orbit*

Number of oscillations per revolution	
radial	13.752
vertical	12.744
Radius of curvature of the ordinary magnets	166.67 m
Radius of curvature of the compensating magnets	297.6 m
Length of the radial focusing magnet	10.99 m
Length of the vertical focusing magnets	10.69 m
Utilization coefficient of the magnetic field	0.8050
Logarithmic derivative of length of orbit by momentum	-3.2×10^{-4}
Angle aperture of the beam	2×10^{-3}

2. *The tolerances of the magnetic field, momentum and magnet assemblage*

Errors in the momentum	0.5 %
Deviations in the field intensity	0.25 %
Deviations in the magnetic field gradient	0.5 %
Deviations in the magnet assemblage	1 mm
Maximum value of the amplitude of the 13th harmonic of the vertical displacement of the magnet	0.05 mm

3. *The main data of the power-supply system*

The rising time of the magnetic field	3.8 sec
Number of cycles per minute	6
Maximum current value	12 000 A
Maximum voltage	8 000 V
Resistance of the magnet coils at 15° C	0.31 Ohm
Maximum value of the inductance of the coils	1.8 He
The peak power	96 000 kVA

4. *The main parameters of the high-frequency system*

The frequency of the accelerating field	
at the beginning of the acceleration	2.624 Mc
at the end of the acceleration	6.063 Mc
The errors in the frequency	
at the beginning of the acceleration	2×10^{-3}
at the end of the acceleration	2×10^{-4}
The corresponding accuracy of the magnetic field measurements	
at the beginning of the acceleration	2.5×10^{-3}
at the end of the acceleration	10^{-2}
The number of synchroton oscillations	
at the beginning of the acceleration	5150 Hz
at the end of the acceleration	24 Hz
Tolerances on the resonance frequency	
at the beginning of the acceleration	31×10^{-7}
at $F = 50$ Hz	4×10^{-8}
at the end of the acceleration	12.5×10^{-9}
Tolerances on the noise-modulation	4×10^{-3} Hz²/Hz

CERN SYMPOSIUM AT GENEVA (11—22 JUNE 1956)

An international symposium on particle accelerators, detection techniques and high energy physics was arranged by CERN between 11 and 22 June 1956. The meetings were held at the Institut de Physique of Geneva University, which had been placed at the disposal of the organisers by the local authorities.

The following countries were represented at the conference: Australia, Belgium, Canada, Czechoslovakia, Denmark, France, Federal Republic of Germany, Greece, India, Italy, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, U.S.S.R., United Kingdom, U.S.A., and Yugoslavia. UNESCO also sent an observer.

The first week of the symposium was devoted entirely to high energy partiele accelerators. During that period, about fifty papers were given on the main problems raised by the construction of modern accelerators, such as the theoretical aspects of the question, the study of magnets, the radiofrequency accelerating system, the injection and ejection of particles, the operation of the machines, etc. Moreover, the technical features of the large accelerators now in operation or in the course of building were explained in detail. Finally, entirely new principles were put forward, whose practical application would considerably improve the already spectacular performance of existing accelerators.

During the second week of the Symposium, attention was focused on detection methods and on the theoretical aspects and experimental techniques of the physics of elementary particles. The seventy papers given dealt with a wide variety of questions, such as Wilson chambers, bubble chambers, over-compression and counting techniques, experimental and theoretical physics concerning mesons, nucleons and antiprotons, quantum field theories, the structure of the proton, mesic atoms, etc.

The exchanges of views that took place between participants, both in and outside the conference room. proved extremely fruitful, and the frankness shown by all concerned bodes well for the possibility of future international cooperation in physics.

[INTERNATIONAL CONFERENCE ON NUCLEAR REACTIONS (AMSTERDAM, 2—7 JULY 1956)

The Amsterdam conference, the full programme of which may be found in No. 2 of this journal (this volume, p. 136), proceeded according to this programme with great punctuality and success. There were more than 500 participants; the contingents from France, Great Britain and the United States were of the order of 70 each, the Soviet group was about 30. This well-planned and well-organised conference made possible a full survey of the rapidly accumulating data from the vast and diversified field of nuclear reactions; the theoretical implications of this information were also extensively discussed. A general conclusion which emerged from the confrontation of all the information is that the optical model of the nucleus is capable to a surprising extent of providing a consistent framework for the analysis of nuclear states over the whole range of so-called 'low' energies. The more fundamental problems of deriving nuclear structures and collective modes of excitation from a many-body theory received due consideration, but these questions are still in an early stage of development.

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